

The Hydrodynamics Laboratory of the California Institute of Technology

By R. T. KNAPP,¹ JOSEPH LEVY,² J. P. O'NEILL,³ AND F. B. BROWN⁴

This paper presents a description of the Hydrodynamics Laboratory and its principal pieces of equipment that have been developed during the last five years. The field of investigations to be undertaken by the Laboratory is presented in general terms.

THE Hydrodynamics Laboratory is an outgrowth of the Hydraulic Machinery Laboratory of the California Institute of Technology.⁵ In the fall of 1941 the Institute was requested to undertake the development and construction of a water tunnel for use in measuring the hydrodynamic forces on projectiles and other underwater bodies. This development was undertaken and the tunnel was put into operation early in the spring of 1942. Such rapid progress was made possible by the use of a large proportion of the apparatus and instruments already available in the existing Hydraulic Machinery Laboratory.

The tunnel has been in continuous operation ever since its completion. In the winter of 1943 it became evident that the equipment and the office and staff facilities were not sufficient for the problems at hand.

Therefore the design and construction of a new building and two additional pieces of major equipment were authorized. Construction of the building was commenced in July, 1944, and it was occupied in the spring of 1945. Design of the two major pieces of equipment, the controlled-atmosphere launching tank and the free-surface water tunnel was started simultaneously with that of the building.

During the war period the laboratory was operated under contract with the Office of Scientific Research and Development for Section 6.1 of the National Defense Research Committee. At the close of the emergency period, the sponsorship of the laboratory was taken over from the OSRD by the Research and Development Division of the Bureau of Ordnance of the U. S. Navy. This sponsorship has been continued and the Fluid Mechanics Branch of the Office of Naval Research has joined with it in the support of the more basic aspects of the current program. In addition to the program carried out under this sponsorship, the Laboratory and its equipment is also utilized for graduate instruction and research within the limitations of its capacity.

Field of Investigations. The primary objective of the Laboratory is to study the characteristics of bodies moving in a fluid. The major emphasis has been placed upon the motion of bodies

in a liquid and in the motion from a gas to a liquid or vice versa. Some of the problems that have been and are being investigated within this field are as follows:

(a) The force systems acting on a moving submerged body, both in the steady and transient states. This includes the investigation of damping forces.

(b) The mechanism of cavitation from conditions of incipient cavitation to the fully developed state in which the cavitation bubble may envelop the entire body.

(c) The effect of shape on the production of cavitation and the development of cavitation-resistant shapes.

(d) The forces acting upon bodies passing through the interface between the gas and the liquid.

(e) Nonsymmetrical forces acting upon submerged bodies traveling close to the free surface.

Many of these studies have the possibility of wide nonmilitary application. For example, the results of the cavitation studies are applicable to ship hulls, propellers, hydraulic turbines, pumps, and flow in closed conduits.

This list in no sense exhausts the scope of the investigations which may be carried on in the laboratory. The equipment is rather unconventional in function and design and can be adapted to the study of many basic problems of interest to the engineering profession.

Building. At the close of the emergency period, plans were initiated to move the water tunnel out of the Hydraulic Machinery Laboratory and into the space provided for it in the new laboratory building. This move has now been completed, thus restoring the Hydraulic Machinery Laboratory to its original capacity for research in its field. The Hydraulic Machinery Laboratory is housed in the west end of the Guggenheim Aeronautics Laboratory. The Hydrodynamics Laboratory forms a south wing directly adjoining it. The new building consists of a sub-basement, basement, and first floor, with direct connection to the corresponding levels in the Hydraulic Machinery Laboratory. Fig. 1 shows the building with the Guggenheim Aeronautics Laboratory in the background. Fig. 2 is a plan of the basement level which shows the distribution of the experimental facilities. The three major pieces of equipment extend to the sub-basement level where, in addition, a well-equipped model and instrument shop is located. The ground floor is used for offices and design. The total available floor space is about 15,000 sq ft.

Laboratory Equipment and Field of Use. At present the Laboratory contains five pieces of research equipment. The three major ones are the high-speed water tunnel, the free-surface water tunnel, and the controlled-atmosphere launching tank. In addition, there is in operation a polarized-light flume and a ripple tank. The high-speed water tunnel is very much like a small wind tunnel except that water is used for the circulating fluid. It is equipped to study the hydrodynamic forces acting on bodies moving in a fluid, or on construction elements of moving bodies and hydraulic machines; for example, control surfaces, guide vanes, propeller blades, etc. The high velocity obtainable in the tunnel (upward to 100 fps), together with the fact that the pressure is controllable independent of the velocity, and that the amount of dissolved air can be controlled, make it particularly suitable for fundamental studies in cavitation.

¹ Director, Hydrodynamics Laboratory, California Institute of Technology, Pasadena, Calif. Mem. ASME.

² Principal Research Engineer, Hydrodynamics Laboratory, California Institute of Technology.

³ Research Engineer, Hydrodynamics Laboratory, California Institute of Technology.

⁴ Research Engineer, Hydrodynamics Laboratory, California Institute of Technology. Jun. ASME.

⁵ "The Hydraulic Machinery Laboratory at the California Institute of Technology," by R. T. Knapp, Trans. ASME, vol. 58, 1936, pp. 663-676.

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FIG. 1 HYDRODYNAMICS LABORATORY

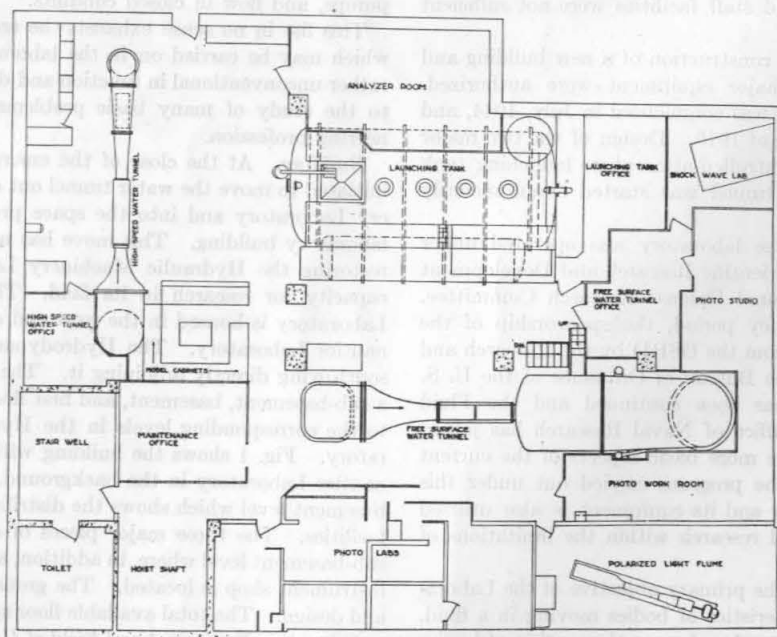


FIG. 2 BASEMENT PLAN OF HYDRODYNAMICS LABORATORY

The free-surface water tunnel is similar in many respects to the high-speed water tunnel. It operates at considerably lower velocity but has a much larger working section. Its distinguishing feature is indicated by its name, that is, the upper boundary of the stream in the working section is an air-water interface. The air pressure is controllable, thus making this apparatus particularly useful for model studies of bodies operating submerged, but very close to the surface. A rather elaborate air-separation system incorporated in the circuit makes it feasible to carry on studies involving the injection of large amounts of gas into the working section.

The controlled-atmosphere launching tank is a large, closed

pressure vessel designed primarily for the study of the hydrodynamic problems involved in the transition period when a free-flying body, initially traveling through air, strikes the surface of a body of water and enters it. The design specifications were all based upon this objective, but the equipment, as built, may be employed in the investigation of other types of problems which require similar facilities. One of these auxiliary uses is the study of underwater explosions, including the effect of the interface on explosions occurring near the surface.

The polarized-light flume is a small low-velocity closed-circuit water channel having a rectangular glass-walled working section. It employs a dilute suspension of bentonite as a working fluid.

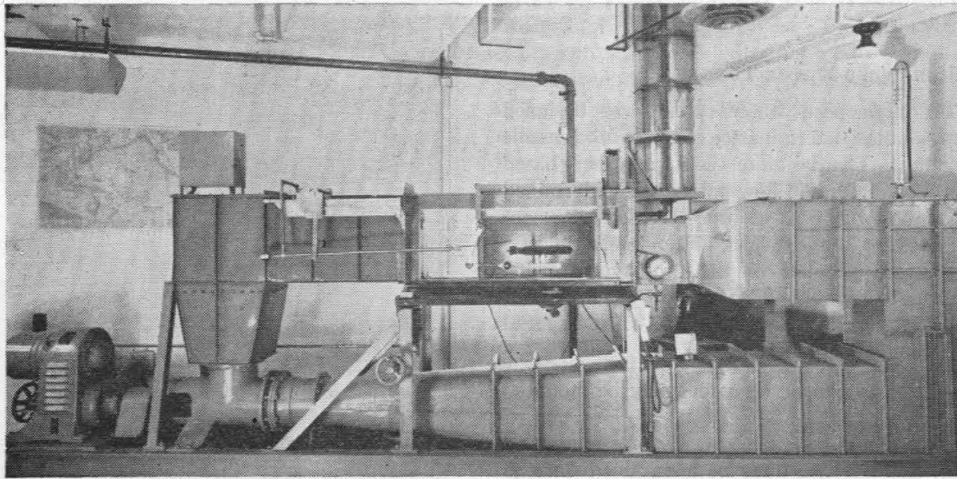


FIG. 3 POLARIZED-LIGHT FLUME

This material has the property of streaming double refraction. This makes it possible to study the flow pattern around any body placed in the working section, since, when the section is illuminated with polarized light, the shear pattern and, by inference, the flow pattern in the fluid becomes visible to the eye. Fig. 3 is a view of the flume, and Fig. 4 shows flow at low velocity around a typical body in the working section.

The ripple tank is a small shallow glass-bottom tank for the study of wave problems. This has proved useful not only in the investigation of surface-wave patterns on enclosed bodies of water, but also, through the good analogy between shallow-water surface waves and pressure waves in compressible fluids, for the investigation of shock waves and other supersonic phenomena in gases. Fig. 5 is a schematic sketch of the ripple tank, and Fig. 6 is a typical record of a Mach-type wave intersection.

The following sections will discuss in more detail the operating

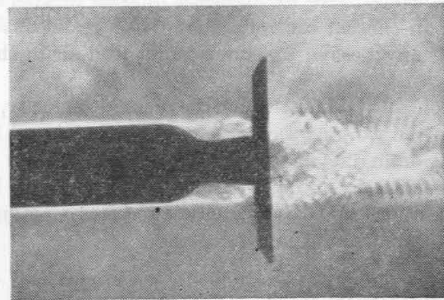


FIG. 4 FLOW PATTERN IN POLARIZED-LIGHT FLUME

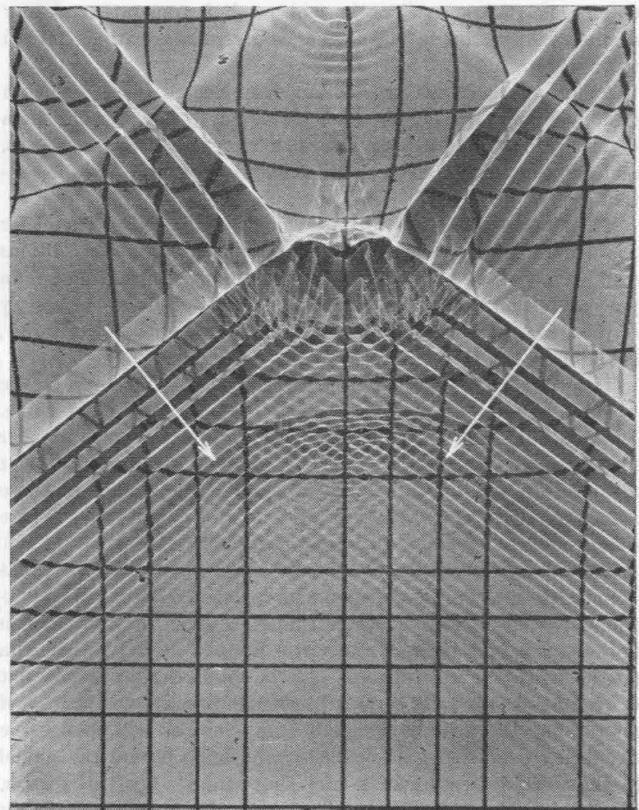


FIG. 6 MACH-TYPE WAVE INTERSECTION

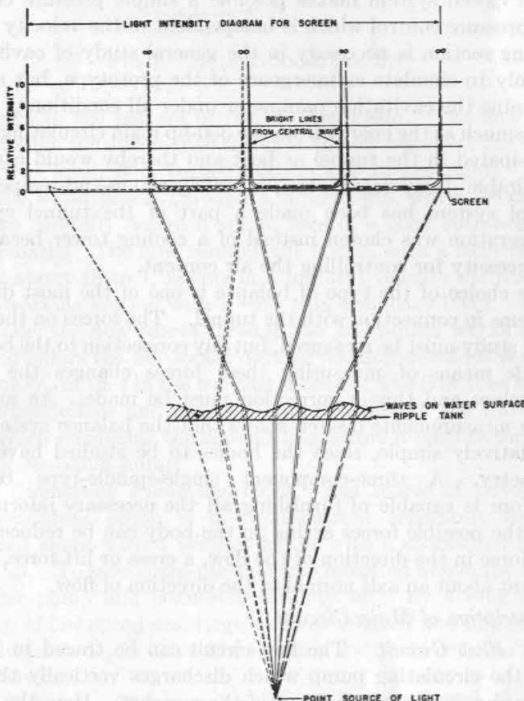


FIG. 5 SCHEMATIC ARRANGEMENT OF RIPPLE TANK

characteristics and construction of the three major pieces of equipment.

HIGH-SPEED WATER TUNNEL

Specifications. The high-speed water tunnel was designed and constructed to permit the determination of the hydrodynamic forces on moving bodies. The design of the apparatus is based on the principle that the forces and flow pattern are determined by the relative flow and are the same whether the fluid is stationary and the object is moving, or vice versa. Therefore, as in wind tunnels, the flow pattern peculiar to the prototype moving through a stationary fluid is simulated by the flow pattern about a stationary model immersed in a moving fluid. The essential components of the tunnel are as follows:

- (a) A working section in which the model may be mounted and observed.
- (b) A circulating system, consisting basically of a pump and piping, by which the flow of water may be maintained through the working section.
- (c) An absorption system, which resorbs any entrained air bubbles.
- (d) An air-content control system which maintains at a constant value any desired amount of dissolved air in the flowing water.
- (e) A control system by which the pressure, velocity, and temperature in the working section can be regulated and kept constant at any desired set of values.
- (f) A balance by means of which the model may be put in different positions and the hydrodynamic forces acting upon it may be measured.

The tunnel design is determined by the size and operating characteristics of the working section. For this tunnel a 14-in-diam working section was chosen with a usable length of 6 ft. The design specifications also call for operation at any desired velocity up to 100 fps, and any pressure from 100 psi to vapor pressure.

A closed type of working section was selected because such a design reduces the energy loss, gives stable flow, results in a definite and calculable boundary correction to the measurements, and makes it possible to control pressure, velocity, and air content easily.

The tunnel has a carefully designed 340-ft path of travel for the water. Such a design avoids external disturbances, obtains a uniform flow in the working section, and permits a minimum power consumption. The effectiveness ratio, that is, the energy of the water in the working section compared with power input, is about $4\frac{3}{4}$ to 1.

The tunnel was designed to give as high a velocity in the working section as possible, considering the power available. High velocity is desirable in order to obtain a Reynolds number for the model which will approach that of the prototype. It also permits cavitation studies at speeds comparable to those associated with the prototype and in a velocity range where dissolved air is less likely to come out of solution.

The ability to control the amount of air in solution is of great help in the study of flow phenomena, particularly that of cavitation. In the high-speed water tunnel, a given air content can be kept constant because the water is not allowed to come in contact with the atmosphere. Air bubbles released as a result of cavitation can be a serious hindrance because the entrained air running through the complete tunnel circuit will change the cavitation conditions, the velocity, and will obscure the model in the working section in a very short time. For this reason, the tunnel has a "resorption" system which resorbs any air released before it has made a complete cycle.



FIG. 7 HIGH-SPEED WATER TUNNEL

The closed system makes possible a simple pressure control. This pressure control which is independent of the velocity in the working section is necessary in the general study of cavitation, not only to simulate submergence of the prototype, but also to determine the cavitation parameter under all conditions.

Inasmuch as the energy from the 350-hp main circulating pump is dissipated in the tunnel as heat and thereby would cause an undesirable temperature rise, a refrigeration-and-temperature control system has been made a part of the tunnel system. Refrigeration was chosen instead of a cooling tower because of the necessity for controlling the air content.

The choice of the type of balance is one of the most difficult problems in connection with the tunnel. The forces on the body under study must be measured, but any connection to the body to provide means of measuring these forces changes the forces themselves and thus a correction must be made. An analysis of the measurements desired shows that the balance system can be relatively simple, since the bodies to be studied have axial symmetry. A three-component single-spindle-type balance therefore is capable of furnishing all the necessary information since the possible forces acting on the body can be reduced to a drag force in the direction of the flow, a cross or lift force, and a moment about an axis normal to the direction of flow.

Description of Main Circuit:

- (a) **Flow Circuit.** The flow circuit can be traced in Fig. 8 from the circulating pump which discharges vertically through the downcomer to the bottom of the resorber. Here the water reverses and flows upward, passes over the top of the partition

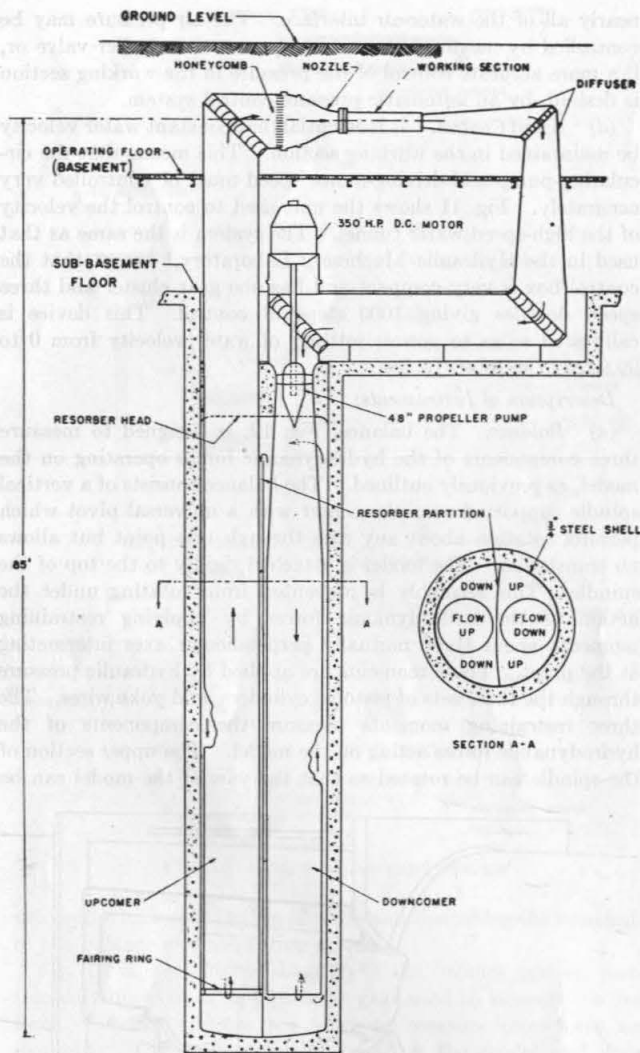


FIG. 8 MAIN TUNNEL CIRCUIT

and down to the bottom of the resorber again. The flow then rises through the upcomer to the vaned elbow where, at the working-section level, it is turned horizontally to the right. From there the water passes through a honeycomb, which, combined with the carefully designed elbow, insures a good entrance flow to the nozzle. The flow through the nozzle, with a reduction in area of about 18 to 1, results in a uniform velocity distribution in the working section with a very thin boundary layer. From the nozzle, the flow passes through the 14-in.-diam working section and enters the horizontal diffuser which reduces its velocity to about $\frac{3}{10}$ of that in the working section. The flow then enters the diffuser elbow and passes downward through the third diffuser which completes the deceleration before it reaches the inlet of the circulating pump.

(b) *Circulating Pump and Drive.* The source of power for the circulating pump is a direct-current separately excited stabilized shunt-wound vertical motor with a short-time rating of 500 hp. To save space the motor is mounted above the 48-in. propeller pump and connected directly to it by a long shaft. A pump of low speed and large size was selected and installed at a considerable depth below the working section in order to avoid pump cavitation.

(c) *Resorber.* The resorber, so-called because its function is to resorb entrained air bubbles into solution, is essentially a

steel tank 11 ft 6 in. diam \times 58 ft long, buried vertically in a concrete pit, the bottom being 70 ft from the level of the sub-basement. The resorber is split into two chambers by a light partition which extends from the bottom to within 4 ft of the top of the tank. A 5-ft-diam pipe extends into each chamber to within 4 ft of the bottom. These are called the downcomer and the upcomer.

The long time required for the water to pass through the resorber, due to its large capacity, plus the high pressure at the bottom, assures complete resorption of any entrained air in the circuit.

There are several additional advantages of this type of resorber construction. The vertical pit saves valuable space and permits a vertical pump drive with no side load on the pump bearings. The resorber, with a volume of approximately 45,000 gal, has a large heat-storage capacity which facilitates temperature control. Finally, the long straight approach of the upcomer gives uniform flow at the upcomer elbow.

Description of Auxiliary Circuits and Control Systems:

(a) *Temperature Control and Refrigeration System.* The refrigeration system used to maintain an even temperature level in the high-speed water tunnel is shown in Fig. 9. A small por-

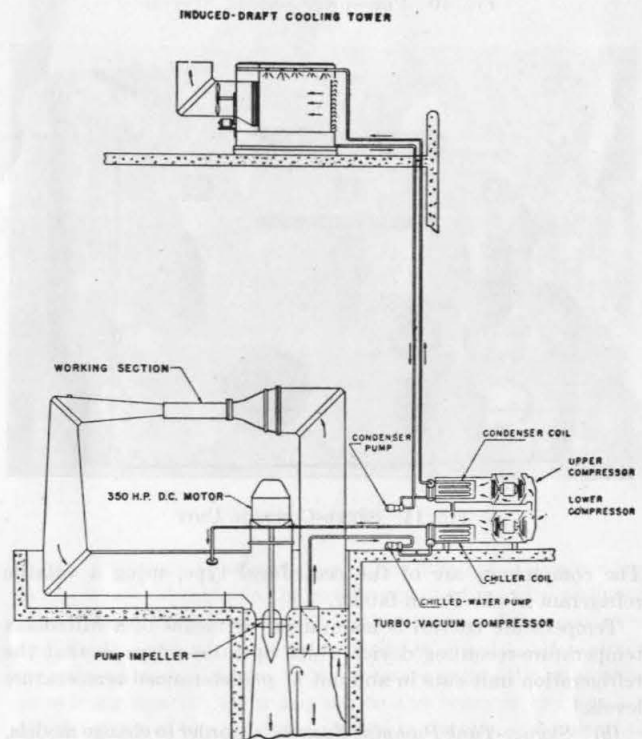


FIG. 9 COOLING SYSTEM

tion of the total volume of water circulated is pulled off the top of the resorber head by the chilled-water pump which forces it through the chiller coil of the refrigeration unit. The chilled water leaves the coil and returns to the main circuit at a point just upstream from the pump elbow. Complete mixture of the cold water is insured by passing through the main circulating pump and through the complete circuit of the resorber. Cooling water for the condenser coil is supplied from an induced-draft cooling tower located on the roof of an adjoining three-story building.

The turbovacuum compressor is a low-pressure self-contained refrigeration unit with the motors hermetically sealed inside.

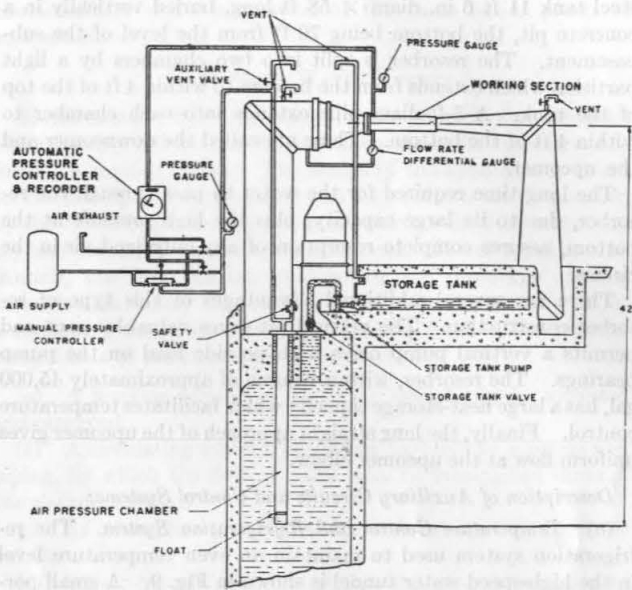


FIG. 10 PRESSURE-CONTROL SYSTEM

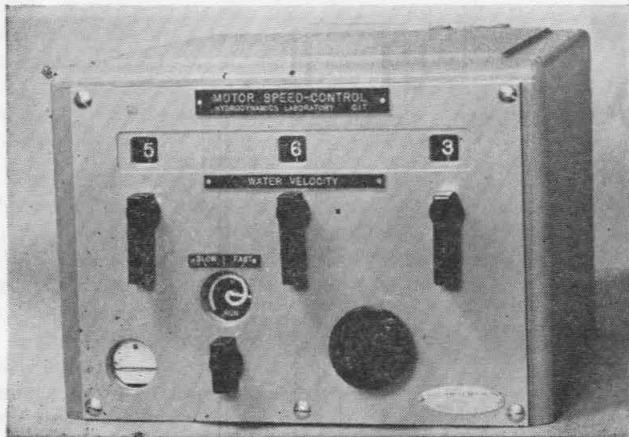


FIG. 11 SPEED-CONTROL UNIT

The compressors are of the centrifugal type, using a volatile refrigerant of the Freon family.

Temperature control is maintained by means of a Micromax temperature-recording device which operates relays so that the refrigeration unit cuts in and out at predetermined temperature levels.

(b) *Storage-Tank Pumping System.* In order to change models, the water level in the tunnel must be dropped to the bottom of the working section. This requires the transfer of 1100 gal of water between the tunnel and a suitable storage tank.

(c) *Pressure-Control System.* The pressure control system and also the storage tank and filling circuit are shown in Fig. 10. The pressure in the working section of the water tunnel is controlled by means of an air chamber with a water level approximately 40 ft below the center line of the working section. By this arrangement, it is possible to use a positive air supply at all times, even when the working section is operating under a vacuum. The relatively large volume of air is also desirable to compensate for changes of volume of the main tunnel circuit due to formation of vapor bubbles during cavitation tests. As Fig. 10 shows, even the minor absorption of air from the pressure chamber has been cut to a minimum by using a float to eliminate

nearly all of the water-air interface. The air pressure may be controlled by means of the manual pressure controller valve or, if a more accurate control of the pressure in the working section is desired, by an automatic pressure-control system.

(d) *Speed Control.* It is essential that constant water velocity be maintained in the working section. This means that the circulating-pump and driving-motor speed must be controlled very accurately. Fig. 11 shows the unit used to control the velocity of the high-speed water tunnel. The system is the same as that used in the Hydraulic Machinery Laboratory,⁵ except that the control box is very compact and has one gear cluster and three speed decades giving 1000 steps of control. This device is calibrated so as to permit settings of water velocity from 0 to 99.9 fps in steps of $1/10$ fps.

Description of Instruments:

(a) *Balance.* The balance, Fig. 12, is designed to measure three components of the hydrodynamic forces operating on the model, as previously outlined. The balance consists of a vertical spindle supported near the center with a universal pivot which permits rotation about any axis through this point but allows no translation. The model is attached rigidly to the top of the spindle. This assembly is prevented from rotating under the action of the hydrodynamic forces by applying restraining moments about three mutually perpendicular axes intersecting at the pivot. These moments are applied by hydraulic pressure through the three sets of pistons, cylinders, and yoke wires. The three restraining moments measure the components of the hydrodynamic forces acting on the model. The upper section of the spindle can be rotated so that the yaw of the model can be

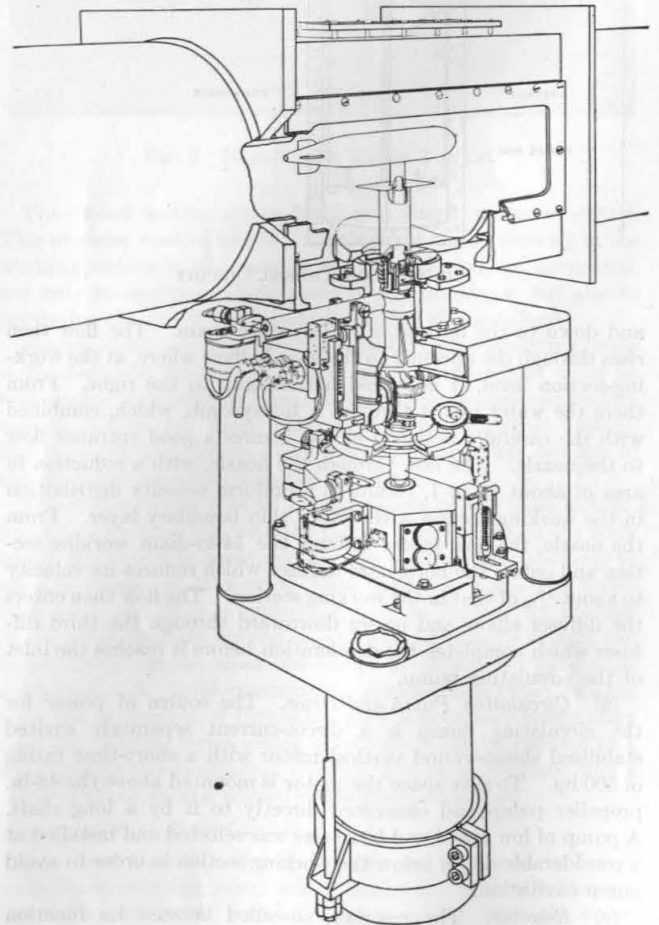


FIG. 12 BALANCE

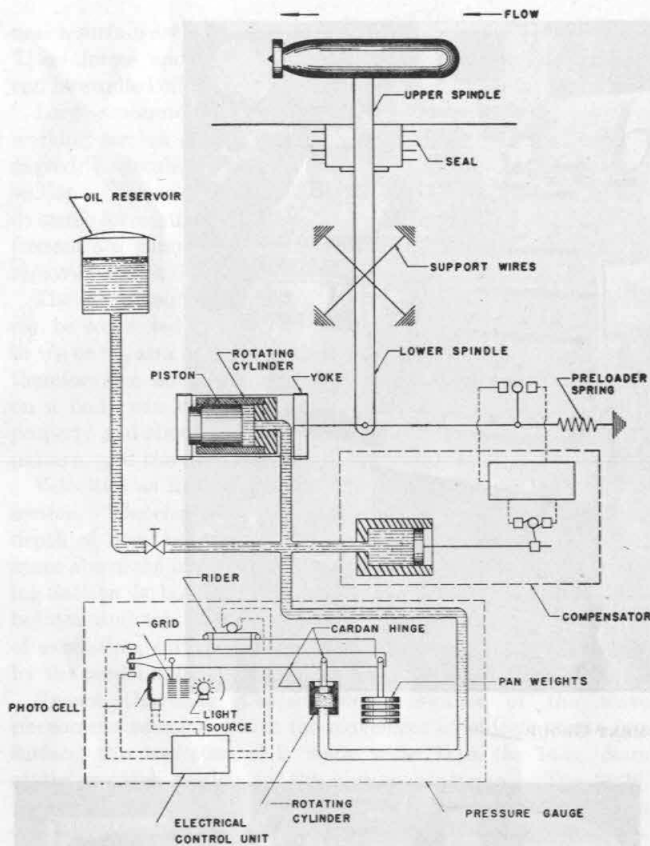


FIG. 13 FORCE-MEASURING SYSTEM

changed with respect to the flow without disturbing the remainder of the balance and measuring system.

Fig. 13 is a schematic diagram of the balance system, force-transmitting system, and pressure gage used to measure the drag force. Similar systems are used to measure cross-force and moment. The hydrodynamic force on the model and upper spindle is transmitted to the restraining wire at the bottom of the lower spindle. The wire and yoke transmit the force to the hydraulic piston. In order to measure positive and negative forces with one piston, a spring preloader is used. To eliminate static friction, the hydraulic cylinders are rotated at constant speed by individual motors.

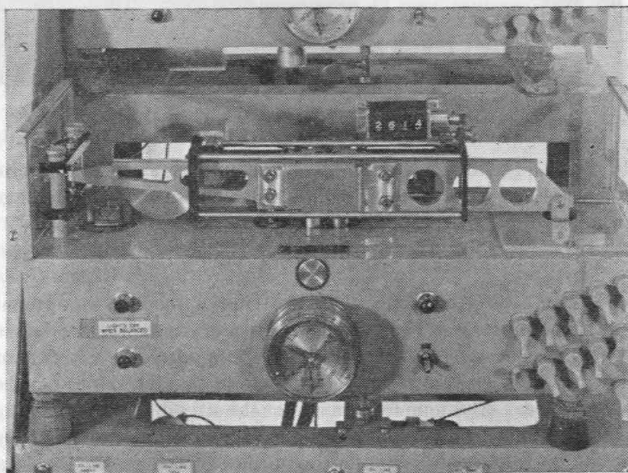


FIG. 14 PRESSURE GAGE

(b) *Pressure Gages.* The pressures in the cylinders on the balance are measured by weighing-type pressure gages, as shown schematically in Fig. 13. Fig. 14 shows one of these gages. It consists essentially of a beam supported on a Cardan hinge pivot. The pressure to be measured is applied through a piston attached to this beam, the piston being fitted in a cylinder which is rotated to avoid static friction, the same as in the case of the balance pistons and cylinders. The force exerted by the oil pressure on the piston is balanced by pan weights applied to the end of the beam and also by a rider weight running on the beam. Unbalance of this beam results in unbalance of the optical-electrical control system which, in turn, automatically moves the rider weight and changes pan weights until equilibrium is obtained. The positions of the rider and pan weights are indicated by counters which read directly in pounds per square inch to the nearest 0.01 psi. The maximum pressure reading is 750 psi.

(c) *Compensator.* The compensator shown in Fig. 15 is a small screw-operated piston which supplies oil to the system in a definite minute amount upon receiving an electrical signal from the balance contacts.

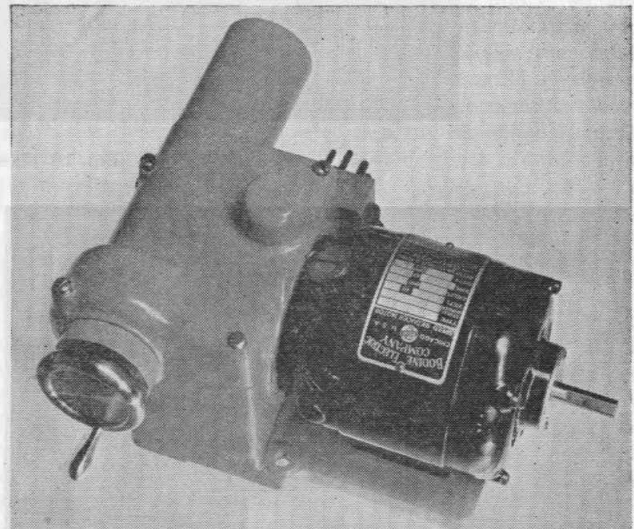


FIG. 15 COMPENSATOR

(d) *Differential Pressure Gage.* The differential pressure gage is employed primarily in the measurement of velocity of flow in the working section by means of the pressure difference across the nozzle, as shown diagrammatically in Fig. 10. It is similar in appearance and design to the pressure gages, the only difference being that the force applied to the beam is the result of the difference of two pressures applied to the opposite ends of the piston. The pressure lines from the nozzle are connected to the bottoms of two separating pots. The lower halves of these pots are filled with water and the upper halves with oil. Pressure leads from the oil domes go to the differential gage.

(e) *Control Panel.* Fig. 16 shows the instrument group with the cross-force, drag, moment, and the differential pressure gages. In the center is a panel with lights indicating the state of balance of the gages and other essential operating data. When all panel lights are out, a condition of gage balance and general instrument readiness is indicated. Thereupon a button is pushed which stops the gage rider motors so that simultaneous pressure readings may be recorded.

(f) *Models.* The models used are exact geometric replicas of the prototypes within the tolerances of the precision machine shops employed. A 2-in. body diameter has been chosen as

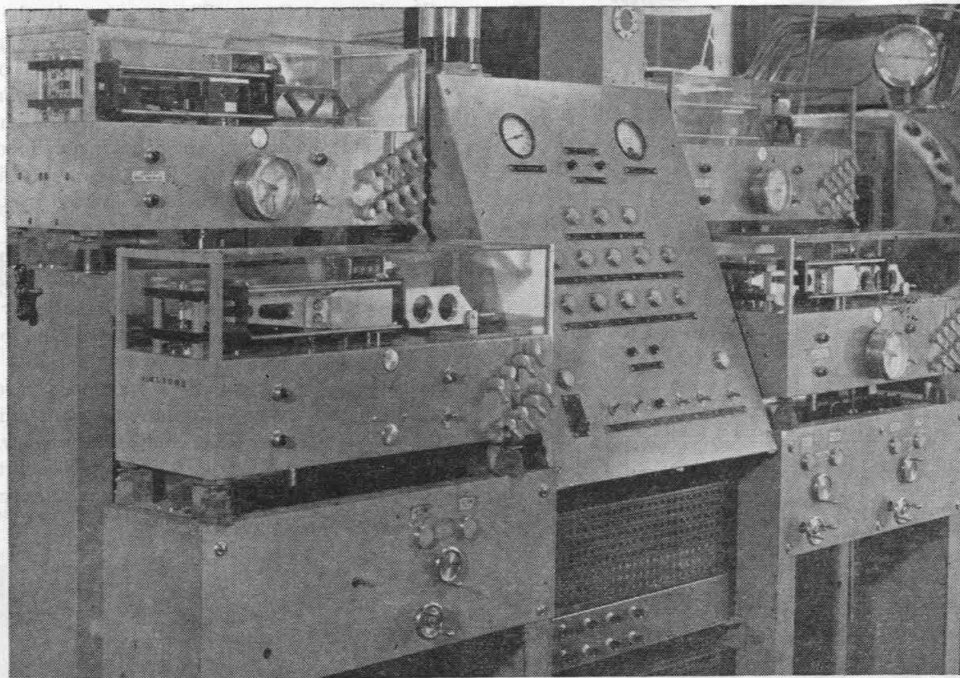


FIG. 16 INSTRUMENT GROUP

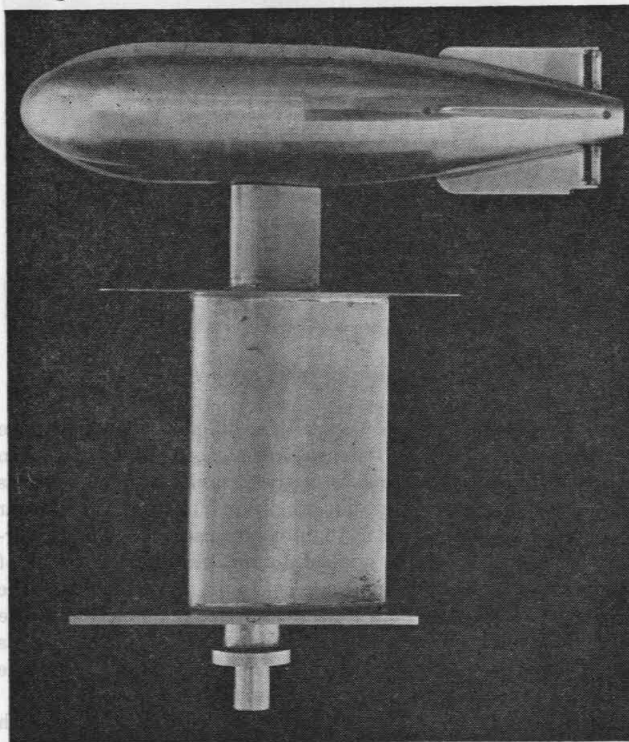


FIG. 17 - TYPICAL MODEL AND SHIELD

standard. Fig. 17 shows a typical model and Fig. 18 its individual components, including the spindle and integral center section. A complete set of cylindrical body sections is available so that any desired length can be assembled from 0.100 in. to 12.000 in. in steps of 0.010 in. When a design of a new body is submitted for test, a quick survey of the model parts shows what elements are available and what new parts must be made.

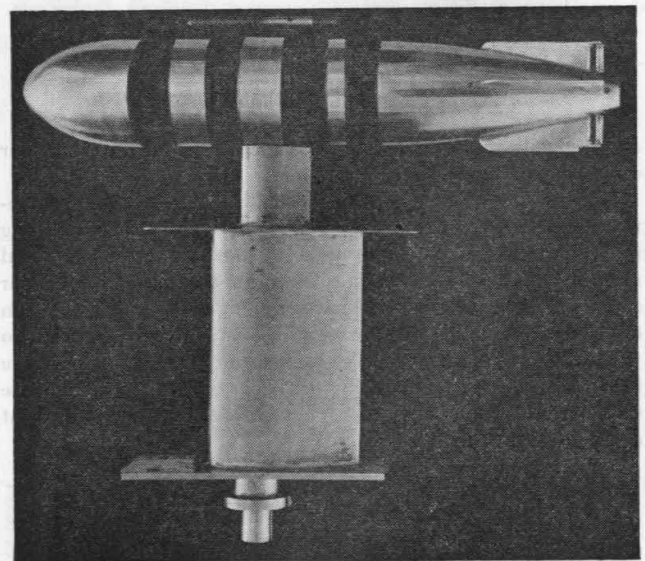


FIG. 18 EXPLODED VIEW OF TYPICAL MODEL

In general, the model parts are made of stainless steel to eliminate corrosion and to secure a reasonable hardness to reduce damage from handling.

THE FREE-SURFACE WATER TUNNEL

General Characteristics. The latest major piece of equipment of the laboratory is the free-surface water tunnel. It offers a working section in which bodies may be supported in a stream of flowing water so that their hydrodynamic characteristics can be determined. A unique feature is that the stream of water passing through the working section is confined by solid boundaries only at the bottom and sides; the top surface of the stream is not a solid boundary, but is here a free surface, i.e., an air-water interface. The hydrodynamic forces acting on a body when it is

near a surface are different from those acting during deep running. These forces and their variation with distance to the surface can be studied effectively in the free-surface water tunnel.

Large amounts of air or other gas may be injected into the working section during certain investigations. If it is not removed, it circulates with the water and returns to the working section. This is not permissible because it affects all the hydrodynamic forces and invalidates the measurements; therefore the free-surface tunnel has a high-capacity air-removal system to remove bubbles before they return to the working section.

The air pressure above the free surface in the working section can be controlled at any value from atmospheric pressure down to $1/12$ or $1/15$ atm. This permits control of cavitation on a model; therefore the effect of cavitation on the hydrodynamic forces on a body can be investigated. It is now possible to model properly and simultaneously the submergence, the surface-wave pattern, and the cavitation characteristics.

Velocities as high as 30 fps can be obtained in the working section. The channel is 20 in. wide and 30 in. deep; the normal depth of flow, however, is 21 in., in order to allow a 9-in. air space above the interface. Throughout its 8-ft length, the working section is bounded by transparent windows on the sides, bottom, and top to permit photographic and visual observation of cavitation, surface configuration, and air entrainment caused by the model under test.

Special Operating Characteristics. Because of the wave phenomena associated with the movement of objects near a free surface, this test channel is made wider than the 14-in. diam of the working section in the high-speed tunnel. The 20-in. width used here should allow the standardized models with a diameter of 2 in. to be used in both tunnels even when the submergence in the free-surface tunnel is so small that the surface-wave phenomena are significant.

Since the top of the free surface must be level before it is disturbed by a model, a rectangular cross section is used. Any other shape would complicate the design of the viewing windows and the accelerating nozzle which precedes the working section. The 21-in. depth of flow where it discharges into the working section will allow a variation in submergence of the model throughout a range from any degree of intersection with the surface to a submergence so great that the free surface does not affect the results.

Continuous operation at velocities as high as 25 or 30 fps can be obtained. For a channel with a depth of 21 in., the critical velocity, i.e., the velocity of a gravity wave, is about $7\frac{1}{2}$ fps. At 30 fps, the ratio of the velocity of flow to the wave velocity will be 4. This ratio, the Froude number for the open channel, is a characteristic parameter describing the behavior of a surface wave in the working section. It is analogous to the Mach number, the flow parameter used with supersonic gas flow.

Another type of surface-wave phenomenon studied by William Froude in 1872, was caused by geometrically similar forms moving parallel to the surface. He found that surface waves of identical geometrical configuration would be produced if the speed-length ratio, V/\sqrt{l} were the same. In adjusting this ratio for geometrical modeling of the surface-wave pattern, values as high as 30 can be obtained for models that are 1 ft long by bringing the tunnel velocity up to 30 fps. By making speed adjustments to produce identical values of V/\sqrt{l} and by providing geometrical modeling of the submergence, the flow pattern around the model should be geometrically similar to the pattern around the prototype. With the 30-fps velocity around a model that is 1 ft long, the Reynolds number will be 3,000,000. This parameter will be high enough in the majority of tests so that exact modeling for skin friction will be considerably less significant than proper modeling of the surface wave.

In order to regulate the cavitation parameter, it is necessary to control the pressure of the air above the water surface. This is done by connecting this space to a high-capacity vacuum pump and regulating the flow of air to the pump with control valves. The valves are positioned by an automatic vacuum regulator. At 30 fps and $1/15$ atm the cavitation parameter is about 0.11.

Arrangement and Construction of the Main Circuit. The free-surface water tunnel has a closed-circuit circulation system which is driven by a propeller pump, powered by a variable-speed direct-current motor. The circuit is arranged in a vertical plane with the working section in the upper horizontal run. The return circuit, containing the circulation pump, is located one floor below the upper level.

Fig. 19 shows a sketch of the entire tunnel. The observer is watching the operation of a model mounted on the balance in the working section. Downstream from the working section, the jet enters a series of vane diffusers which increase the cross section and decrease the velocity. The low-velocity flow enters an air separator which can be seen through the cutaway opening in the upper left-hand corner of the sketch. At the lower level, the discharge from the pump goes into a circular diffuser section which again decreases the velocity. At the maximum diameter, a transition section gradually changes the cross section from round to square. The acceleration of the flow to the working velocity begins in the vertical riser, continues in the accelerating elbow above this riser, and is completed in a two-dimensional nozzle which discharges a 20-in-wide \times 21-in-deep jet of water into the working section.

Since the working section may be operated at very low pressures, the entire structure is designed to support an external pressure of 1 atm. This requires heavy strengthening ribs on all the exterior surfaces where the cross section is not circular.

Construction of Working Section. All faces of the working section shown in Fig. 20 contain lucite windows which are held in a comparatively light steel framework. Deflection of this framework allows the windows to take a share of the stresses involved in the low-pressure operation. The pressure on the top and bottom windows loads the side windows in a vertical direction and vice versa. Positive pressures must be limited to a few pounds per square inch because the windows do not assist in taking the load in such cases. In order to limit deflections, the 30-in-high side windows are $4\frac{1}{2}$ in. thick, and the 20-in-wide top and bottom windows are 3 in. thick. The length is divided into two sections in order to decrease the size of the lucite castings.

Deceleration Downstream From Working Section. The velocity must be reduced before the flow enters the air separator since time must be allowed for the bubbles to rise. The purpose of the diffuser is to take the water discharged by the working section and distribute it evenly over a cross-sectional area about 16 times as great, thereby reducing the velocity by this ratio.

An efficient diffuser should regain a large portion of the difference in the velocity heads at the entrance and discharge. A number of factors complicate the problem of getting efficient diffusion in the free-surface water tunnel. There is a transition from an open surface to a closed diffuser. The size of the laboratory precludes the use of the customary long diffuser with a gradual expansion. Air bubbles in the flowing stream tend to prevent the flow from following the expanding channels; furthermore, work must be done in compressing these bubbles through the pressure regain obtainable. The necessity for a free surface in the air separator makes it difficult to apply the pressure across the diffuser which is required to realize whatever head the diffuser is capable of regaining.

A short diffuser with reasonable efficiency was secured by taking the flow through a series of four 60-deg turns with vane dif-

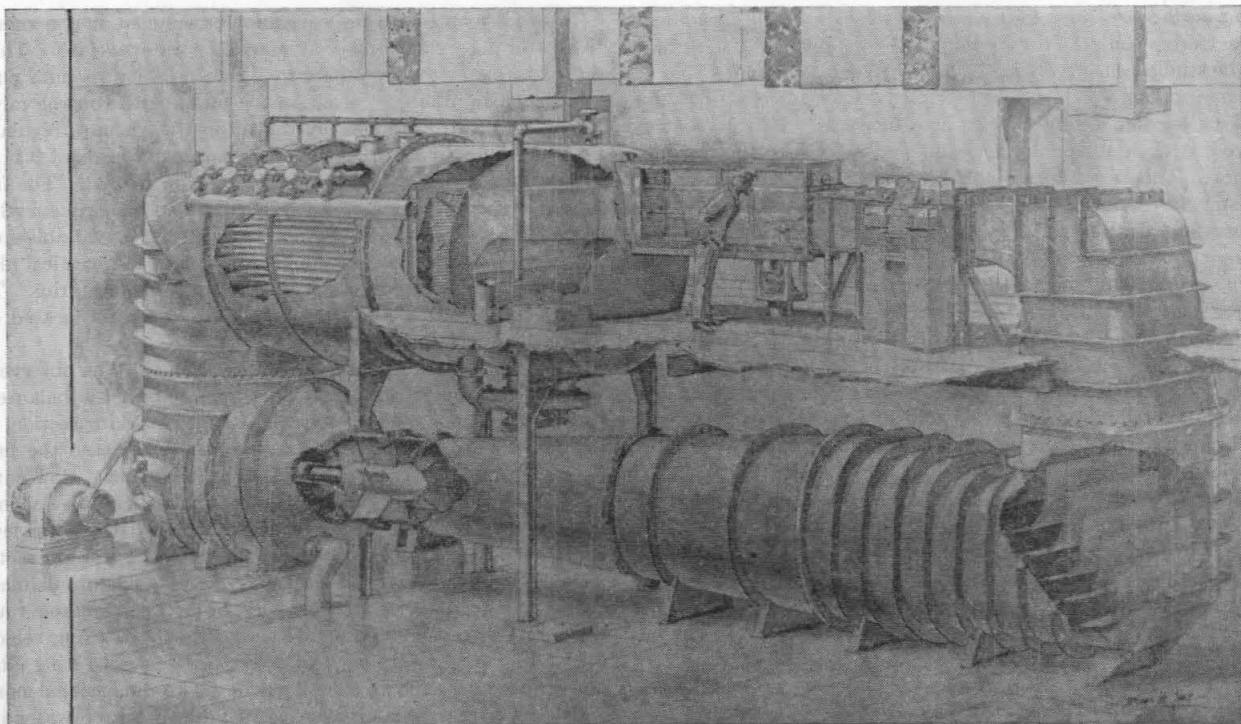


FIG. 19 FREE-SURFACE WATER TUNNEL

fusers which double the cross-sectional area at each turn. The vanes are curved on a 4-in. radius and the spacing transverse to the stream is small.

A regain of velocity head by the diffuser implies that the downstream pressure is higher than the upstream pressure. Since there are free surfaces on both sides of the diffuser, this pressure difference is maintained by adjusting the downstream level a few inches above the working-section level and by holding the air pressure above the air separator at a higher value than the air pressure in the working section. The total pressure across the diffuser, i.e., the head regained, is equal to the air-pressure difference plus the small surface-level difference between the air-separator chamber and the working section.

Pressure Controls. The working-section pressure can be controlled from atmospheric pressure down to about $1/15$ atm. Control valves are installed in the line connecting the working-section air chamber to the vacuum pump. They are actuated by a drift-compensated proportional controller, having a measuring element which is sensitive to the pressure in the working section. To simplify the control system, a manually controlled air bleed into the working section is provided. This makes it possible for a single automatic control system which operates valves in the vacuum line only to make pressure adjustments in both directions.

Air that is injected for powered models will enter the chamber above the air separator in varying amounts. Adjustments of the pressure in this chamber are made with control valves which are installed in the air-exit line. This line can be connected either to the working section or to the vacuum pump. Here again, manually controlled inbleed of compressed air is provided for changing operating conditions and for use, when necessary, in positioning the automatically controlled air-exit valves within their operating range. The controller operating these valves therefore is able to maintain the required back pressure on the diffuser.

The regulators for both the working-section pressure and the

release of air from the air separator are shown on the control panel at the left in Fig. 20. The air piping and control valves can be seen in Fig. 21.

The Air Separator. The air introduced in the working section will at times appear in the form of small bubbles, many of which may be deeply submerged. The rate of rise of such bubbles is rather low. This means that either a long time or a short distance to a free surface is required for adequate separation. Although the velocity at which the flow leaves the battery of deceleration vanes will probably be under 2 fps, the depth will be very great—too great to permit the rise of a small bubble to the surface before the flow reaches the vane elbow and turns down toward the circulating pump. To reduce the effective depth, the air separator is divided into a series of shallow channels by means of a spaced stack of trays which have solid tops and perforated bottoms. The perforations permit free access of any bubble to the space within. This space contains dividers which permit the trapped air to flow across the stream to channels leading upward to the surface of the pool above the stack. Fig. 22 shows some of the trays after installation. They are $1/2$ in. thick and have a net separation of about 2 in. The minimum time required for the flow to pass through the tray section will be approximately 5 sec. Bubbles with an effective rate of rise of $2/5$ ips or greater will reach the perforations and be trapped. To assist the bubbles to separate there is a small flow from the main stream up through the perforations and out through the channels to the risers. This flow is induced by taking water from the pools above the trays (see one of the suction nozzles at the top of Fig. 22) and pumping it back into the main circuit between the diffuser vanes and the air-separator trays, i.e., just upstream from the air separator.

Many of the investigations may produce splash and spray above the free surface in the working section. Provisions are made to collect the water thus involved by skimming off the top layer and deflecting it to each side where it can drop into a stilling pool below the diffuser. From the stilling pool the skimmed

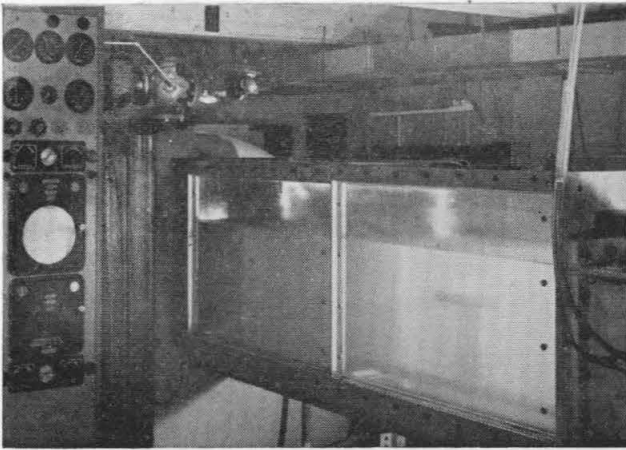


FIG. 20 WORKING SECTION AND AIR-CONTROL PANEL

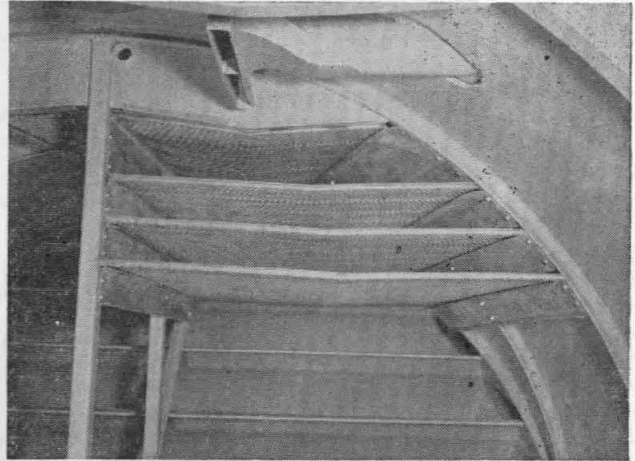


FIG. 22 ENTRANCE TO AIR SEPARATOR WITH UPPER FOUR TRAYS INSTALLED

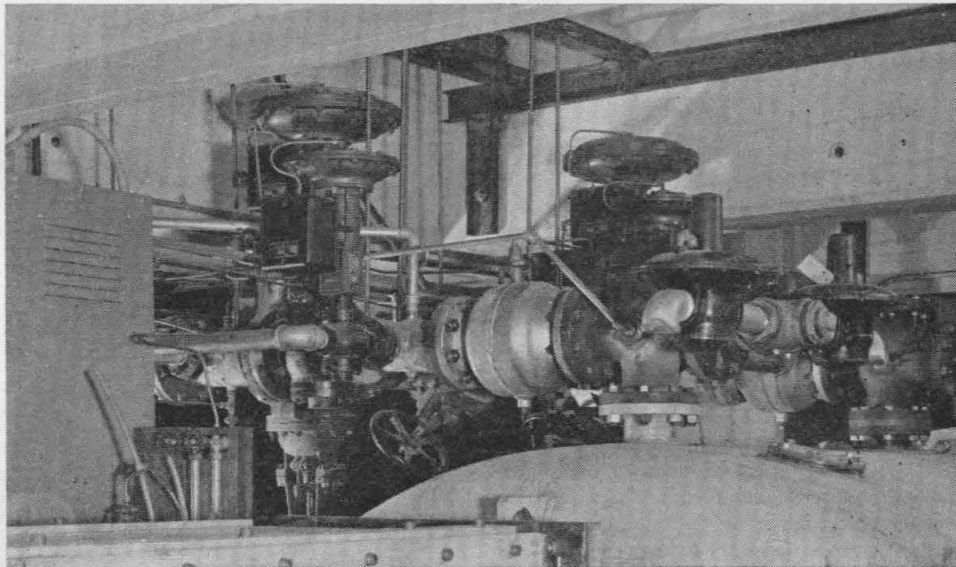


FIG. 21 AIR PIPING AND CONTROL VALVES

water is pumped back into the main circuit just upstream from the air separator. Entry at this point will give the air separator a chance to take out any remaining bubbles. The speed of the pump which takes the water out of the stilling pool is adjusted by a controller that is sensitive to the water level. By keeping this surface level fixed, the total water in the main circuit is practically constant, and this third free surface does not affect the operation of the main circuit.

Main-Circuit Pump and Driving Motor. A standard 42-in. propeller pump is used to circulate the water. The bearings are arranged for a horizontal drive and the shaft seal is designed for pressures acting in either direction, since the submergence is not sufficient to maintain a positive seal pressure during high-vacuum operation in the working section. Although this pump circulates approximately the same quantity of water as the one in the high-speed tunnel, the power requirements are greatly reduced because of the lower head required to produce the lower velocity in the working section. Therefore the pump of the free-surface tunnel is driven by a 75-hp direct-current motor which is powered with a 75-kw rectifier. The speed is con-

trolled by a system which is identical with the one used in the high-speed tunnel.

Measurement of Hydrodynamic Forces. In order to determine the hydrodynamic characteristics of a body, it must be supported in the stream of flowing water by means of a balance capable of measuring the resultant forces. Since the forces resulting from tests in a free-surface channel have components that are different from those previously obtained, and since the position of the model relative to the interface should be adjustable, new balance systems are being developed for the free-surface water tunnel.

For most craft which operate at or near a free surface, variations in the pitch angle and degree of immersion greatly influence the resultant forces on the body. A great deal of valuable information can be obtained in the free-surface tunnel when models are supported with zero yaw. If the pitch angle is varied while maintaining zero yaw, a three-component balance, which measures drag, lift, and pitching moment, will define adequately the forces on models that are symmetrical about the drag-lift plane. Although in some investigations such a three-component

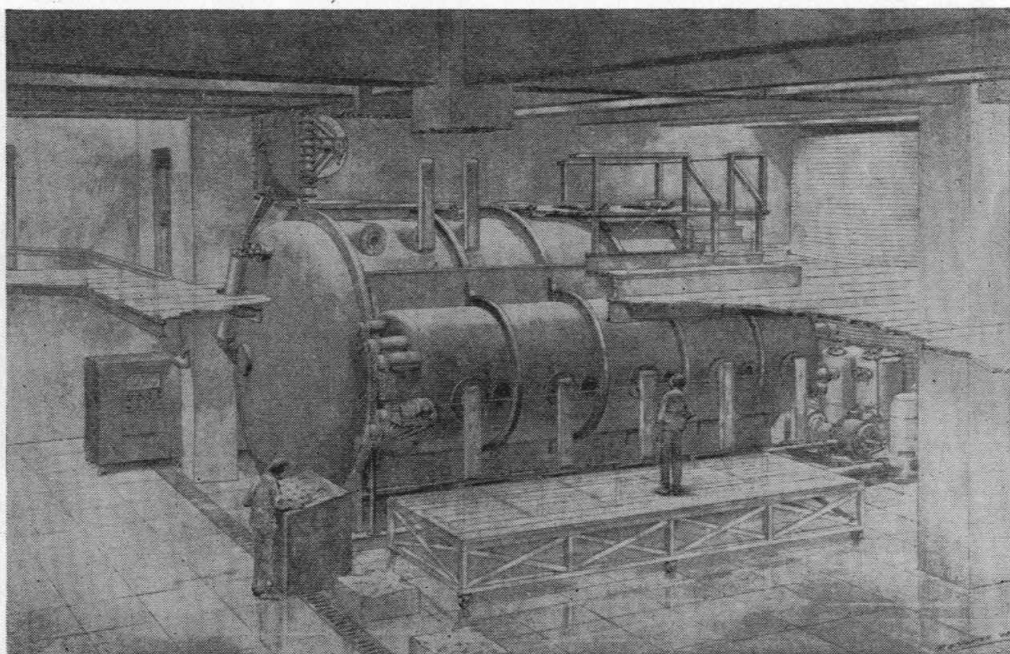


FIG. 23 GENERAL VIEW OF CONTROLLED-ATMOSPHERE LAUNCHING TANK

balance will secure all the information desired, its design and operation are considered only a part of the development of a five- or six-component weighing system. Six components will be necessary, in fact, before the balance can be considered complete, because even the rolling moment induced by yaw is significant for laterally steerable craft operating at or near a free surface.

CONTROLLED-ATMOSPHERE LAUNCHING TANK

General Description. The primary use of the controlled-atmosphere launching tank is in the study of the hydrodynamic problems involved as a free-flying body enters the water from the air. The equipment may be used for other studies, such as underwater explosions, which require similar facilities. In studying hydrodynamic phenomena occurring at an interface between a liquid and a gas, it is sometimes necessary to have control of the atmospheric pressure and density. For this reason the tank was built as a completely enclosed pressure vessel.

Fig. 23 is an artist's sketch showing an over-all view and Fig. 24 is a cutaway view of the launching end of the tank. The tank itself is a completely enclosed pressure vessel of welded-steel construction. In normal operation, the tank is filled with water to about three fourths of the total depth, leaving an air space above the water. A centrifugal launching device, mounted on the underside of a large hatch cover, launches the model under investigation at any desired trajectory angle from vertically downward to horizontal, with any pitch angle up to ± 10 deg, and at any desired speed up to 250 fps. A battery of high-speed motion-picture cameras records the path of the model during both the air flight and the underwater travel. The cameras operate without shutters, and exposures are made by intermittent illumination of the interior of the tank with Edgerton-type flash lamps. The fields of view of adjacent cameras overlap by 60 per cent, so that at least two cameras photograph the model throughout its travel. The stereoscopic vision thus obtained makes it possible to recreate the path of the model step by step with the analyzing equipment which will be described later.

In Fig. 24 the launcher is seen in the launching position

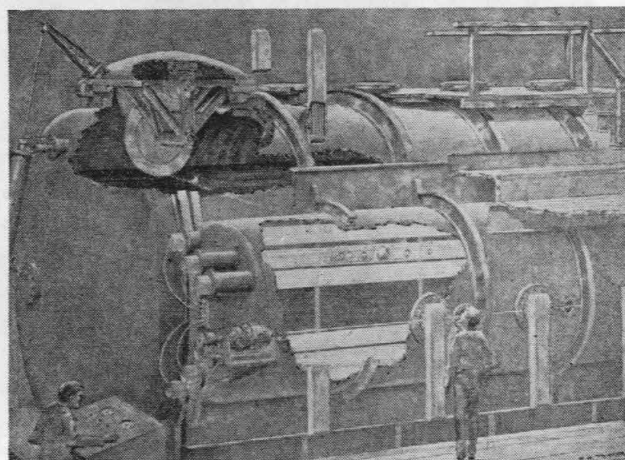


FIG. 24 CUTAWAY VIEW OF LAUNCHING END OF TANK

shortly after having released a model, and the model is seen entering the water. The air-trajectory cameras are approximately level with the launcher and slightly to the right. Four of the five underwater cameras are shown on the lower level. The flash lamps for illuminating the interior of the tank are installed in the six lucite tubes which pass through the tank, above and below the underwater cameras.

For convenience in description, the equipment will be subdivided into four components, namely, the tank, the launcher, the trajectory-recording system, and the data-analyzing system.

The Tank. The physical requirements for the study, as indicated in the previous section, call for control of the air pressure above the water in the tank. For this reason the tank was designed to withstand an external pressure of a full atmosphere and an internal pressure of 40 psi. The tank provides a clear launching plane 25 ft long with a water depth of 10 ft.

The tank structure, as may be seen in Fig. 25, consists of a large horizontal cylinder, 13 ft diam and 29 ft long, to one side of which is attached a section of a smaller cylinder 6 ft diam and

23 ft long. The purpose of the smaller cylinder is to provide the necessary distance from the cameras to the launching plane so that the launching plane can be covered with a reasonable number of cameras. The large openings in the shells of the two cylinders where they are joined together, require special provisions for carrying the hoop stress across the opening. This is done by means of the longitudinal T beams, 20 in. high, running the full length of the intersection, and 2-in. \times 12-in. vertical columns spaced at 54-in. intervals which span the opening and transmit the load from one T beam to the other. These columns are spaced so that they will carry the load without ec-

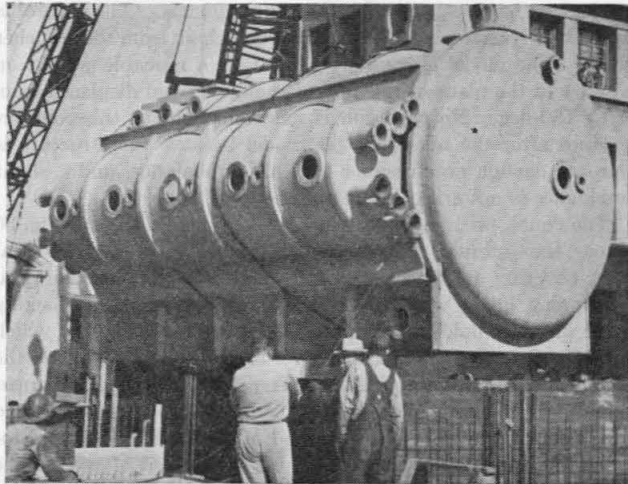


FIG. 25 CONTROLLED-ATMOSPHERE LAUNCHING TANK BEING LOWERED INTO BASEMENT FOR INSTALLATION

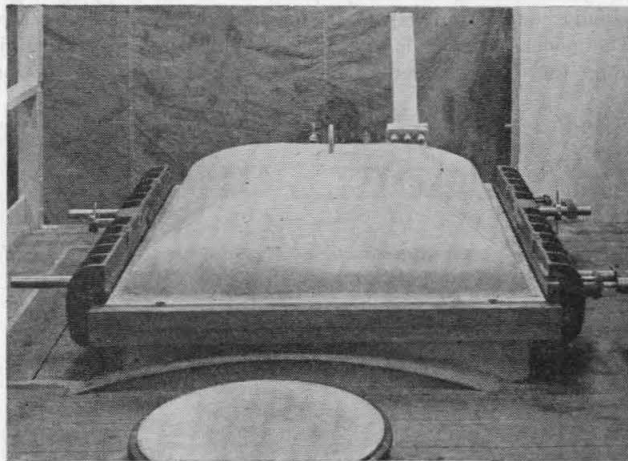


FIG. 26 HATCH COVER AND C-CLAMPS

centricity and at the same time stay out of the field of view of the recording cameras. The weight of the empty tank is approximately 40 tons, and when filled with water to a depth of 10 ft, the combined weight is about 150 tons.

The large rectangular hatch opening, which may be seen in Fig. 25, on top of the tank and near the far end, is off center to increase the distance between the launching plane and the cameras. The entire launching mechanism is mounted on the hinged cover which has an O-ring pressure seal. A hydraulic cylinder provides for rapid opening and closing of this hatch cover. Heavy C-clamp frames along the two longitudinal edges of the opening hold the cover rigidly in place during operation of the launcher.

Fig. 26 shows the hatch cover, with the clamps and the opening lever. Four flanged openings along the top of the main cylinder are for access and recovery of models, ten on the side and ends are for attachment of recording cameras, five for visual observation windows, twelve for insertion of the lucite tubes which house the lamps, and two for control of the air pressure.

Since the tank is used for underwater photography, it is extremely important to maintain the water in it at a high degree of clarity. The lamps and the cameras are both on the same side of the tank. The light has to travel an average water path of 24 ft in going from the lamps to the model and back to the cameras. It is obvious that even a slight amount of color, fine suspension, or microscopic life in the water would absorb or scatter most of the light before it reached the cameras. Therefore the treatment of the interior of the tank was given a careful study. The requirements were to prevent corrosion of the steel tank, to avoid contamination of the water in any manner which might impair its optical properties, to provide a dark background, and to minimize the possibility of damage to models striking tank walls. Very few materials were found which could meet all these requirements. The one finally selected is a polyvinyl chloride plastic (Koroseal) which is cemented all over the interior of the tank, in

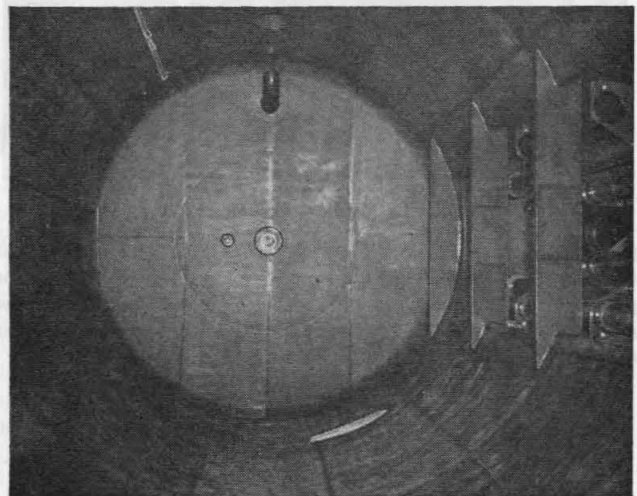


FIG. 27 INTERIOR OF TANK SHOWING TANK LINING, OVERHEAD ULTRAVIOLET LIGHT WITH COLUMNS, AND LUCITE TUBES AT RIGHT

sheets $\frac{3}{32}$ in. thick, with the seams between sheets heat-sealed with strips of similar material. Commercial sand and alum filters remove suspended materials from the water, and a string of germicidal ultraviolet lamps installed along the ceiling control bacterial growth. A vacuum pump is provided for controlling the atmospheric pressure. Fig. 27 shows the lined interior, the ultraviolet-light tubes along the ceiling and, incidentally, the reinforcing columns at the junction of the two cylinders and some of the lucite tubes in the smaller cylinder. Occasionally the local water supply contains traces of yellow coloring matter in solution which cannot be removed by filtration. This makes the water completely unusable in the tank since it filters out all the blue and violet light in which the flash lamps are rich. The difficulty has been overcome by distillation, which is done rather economically by means of vapor-compression stills.

The Launcher. The design specifications for the launcher call for a device which will produce accurately any desired speed up to 250 fps, be compact so it may be lowered easily into the tank for launching and brought out for loading and setting, and which will launch models with pitch angles (angle in vertical

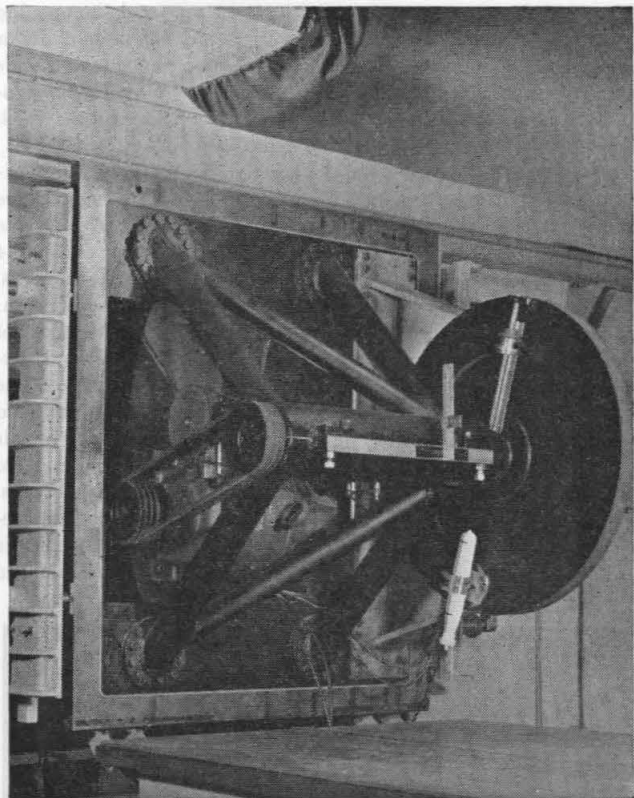


FIG. 28 LAUNCHER MOUNTED ON OPEN HATCH COVER

plane between axis of model and path of the center of gravity of the model) up to ± 10 deg. It was also desired to provide for possible modification to include pitch angular velocity and yaw angles. After an extensive consideration of the possible launcher types, it was decided to use a centrifugal launcher.

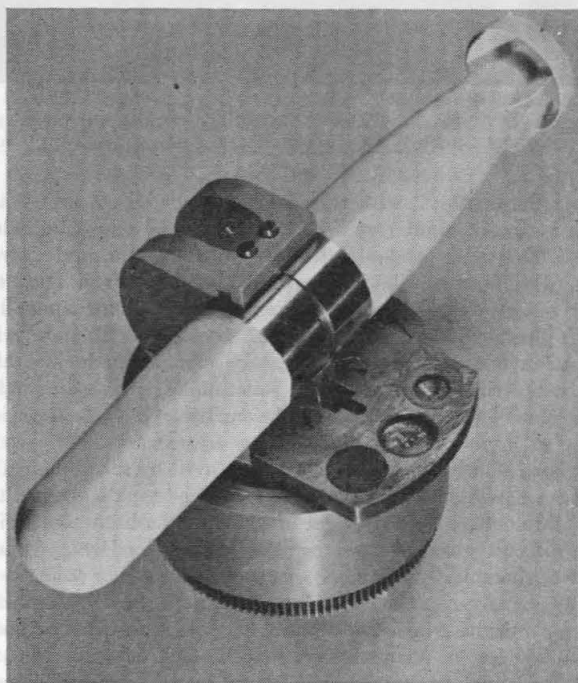


FIG. 29 CHUCK WITH MODEL

The launcher consists basically of a rotating wheel which carries the model near its periphery, with a planetary-gear system to prevent the model from rotating about a transverse axis as it goes around with the wheel, and with a mechanism for releasing the model at any predetermined point along a 90-deg arc. Fig. 28 shows the launcher mounted on the open hatch cover with a model in place in the chuck. The wheel is a heavy steel plate having sufficient flywheel effect to insure uniform velocity. It is supported on a stainless-steel shaft which is mounted on four preloaded precision ball bearings, assembled in a quill to form an accurately aligned unit. The launcher is driven by a 10-hp d-c motor whose speed is controlled electronically by a device similar to the ones used with the water tunnels. The control is activated by a selsyn generator driven by chain from the launcher shaft. The model is counterbalanced by a movable weight on a screw in the plane of rotation of the model and displaced from it by 180 deg. No provision is made for shifting this counterbalance after the release of the model because the structure is massive enough not to suffer from this unbalance, and a slight unbalance is not critical once the model is free.

The chuck, with model in place, is seen in Fig. 29, and Fig. 30 shows the internal construction. It consists of a cylindrical seat, covering a 135-deg arc, into which the model is laid, and a gripping finger which holds the model in place. A locking lever, in turn holds the gripping finger against a spring which tends to open it. The locking lever extends slightly beyond the face of the wheel on the far side. To release the model, a tripper block is moved by a solenoid into the path of the protruding end of the locking lever. The open end of the model seat faces toward the periphery of the wheel. At the instant of release the model and the chuck have identically the same motion. From this instant the model moves along a tangential path, and the chuck, continuing its circular motion, gradually lifts away from it. After release, the heavy spring moves the gripping finger rapidly out of the way of the model to prevent interference. The model seat is made as rigid as possible to reduce to a minimum the energy stored in it which might affect the motion

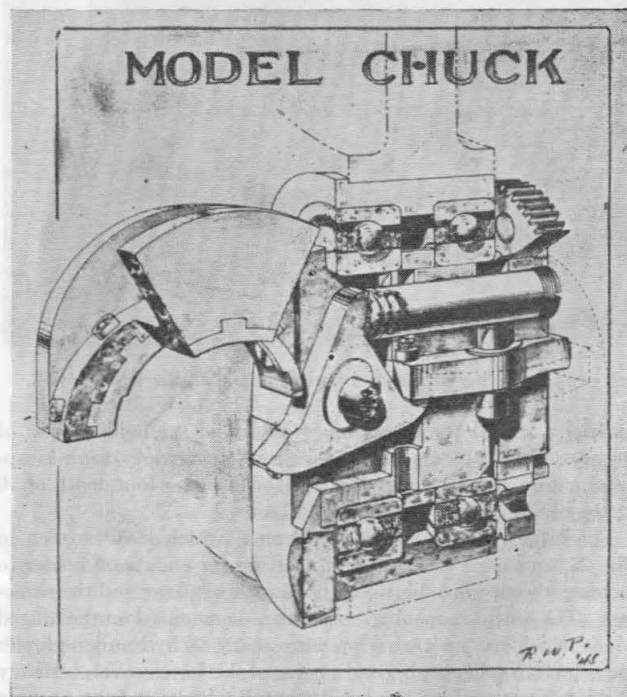


FIG. 30 INTERNAL CONSTRUCTION OF CHUCK

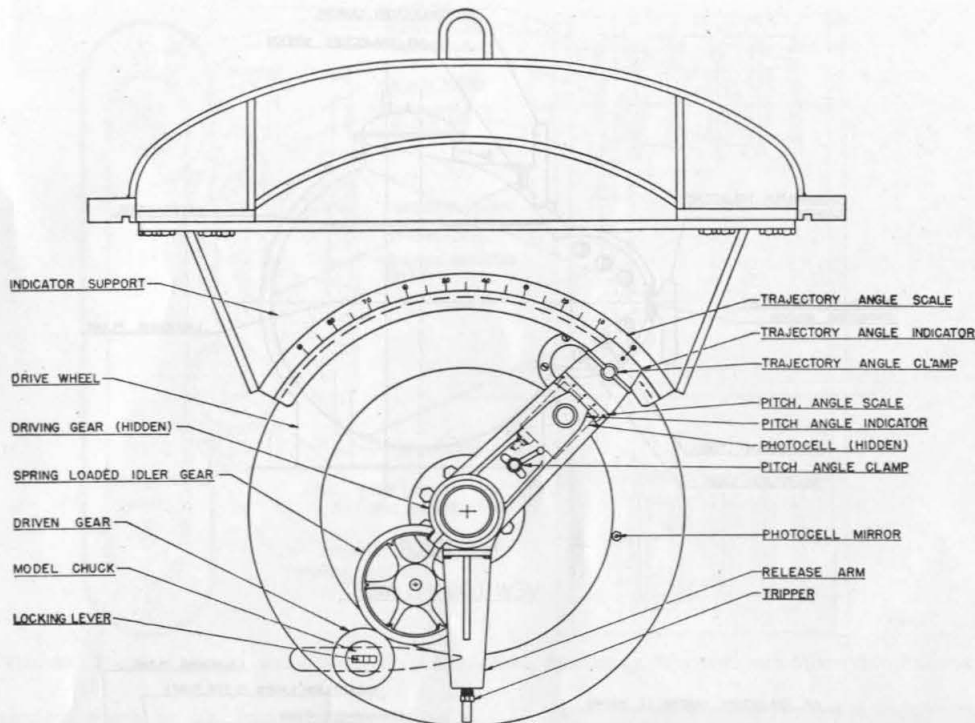


FIG. 31 MODEL LAUNCHER, CONTROL SIDE

of the model at the instant of release. The entire chuck mechanism is mounted in precision ball bearings.

Fig. 31 is a drawing of the launcher showing the opposite face of the wheel with planetary-gear system and launching controls. The planetary-gear system, which prevents the chuck from rotating around its own axis, is composed of specially cut fine-pitch precision gears. To insure smoothness of operation and to prevent backlash, the idler gear of this train is made in three layers. The central layer is integral with the spokes and hub. The two outer layers are ring gears and are loaded against the central layer by small tangential coil springs in the rim. The central layer and one outer layer mate with the hub gear, while the central and other layer engage the chuck gear. The hub and chuck gears are equal in diameter. There are two levers or arms, both bearing-mounted on the wheel shaft and prevented from rotating by clamps. The trajectory-angle arm clamps to the trajectory-angle scale, has a 90-deg adjustment, and is integral with the release arm which carries the solenoid-operated tripper. The pitch-angle arm is attached to the central gear of the planetary system, and is clamped to the trajectory-angle arm with an adjustment of ± 10 deg on the pitch-angle scale.

When the trajectory-angle arm is set at zero on its scale, the release arm hangs vertically down, and therefore would release the model on a horizontal trajectory. If, at the same time, the pitch-angle arm is set at zero on its scale, the axis of the model will be horizontal, i.e., parallel to the tangent at the point of release, and the model would fly with zero pitch angle. Now, if the trajectory-angle arm is moved a given number of degrees to any new position on its scale while leaving the pitch-angle arm clamped to it, then the release point is shifted the same number of degrees and the central gear is also rotated the same number of degrees in the same direction. The result is that the axis of the model is now parallel to the tangent at the new release point, and if released, the model would again travel with zero pitch. If, on the other hand, the trajectory-angle arm is left clamped while the pitch-angle arm is shifted, say, 5 deg, then the

release point remains unchanged, whereas the model axis now makes an angle of 5 deg with the tangent at the release point. Thus the model would take off with a pitch angle of 5 deg.

On the trajectory-angle arm, on the side facing the wheel, there is a light source and a photocell. A small mirror mounted on the wheel reflects the light into the photocell every revolution when the chuck is about 20 deg before the launching point. This transmits a signal to the electronic interlocks which synchronize the operation of the tripper with that of the cameras and the lights.

Trajectory-Recording System. The cameras and flash lamps of this trajectory recording system have been described recently;⁶ therefore only a brief description of this equipment will be given here.

In this installation the cameras are used as precision-measuring instruments, and many of the special features incorporated in their design were dictated by this requirement. To obtain all the necessary data from each launching, the camera system was designed to cover the entire underwater volume of the tank, as well as the above-water portion containing the trajectory from the launcher to the water surface. Since an entire test run occurs in 1 sec or less, it was decided that photographs should be taken at rates varying between 500 and 3000 per sec, per camera, depending upon the launching speed and the accelerations anticipated during a particular run.

The recording system consists of a battery of synchronized high-speed motion-picture cameras using standard 35-mm film. The main bank of five cameras records the underwater trajectory, while another bank of two or three cameras is used for recording the air trajectory. The optical coverage of the cameras is shown in Fig. 32. At the launching plane the adjacent camera fields have a 60 per cent overlap. In the vertical direction the field of view covers the entire water depth. This multiple cover-

⁶ "Special Cameras and Flash Lamps for High-Speed Underwater Photography," R. T. Knapp, *Journal of the Society of Motion Picture Engineers*, vol. 49, no. 1, July, 1947, pp. 64-82.

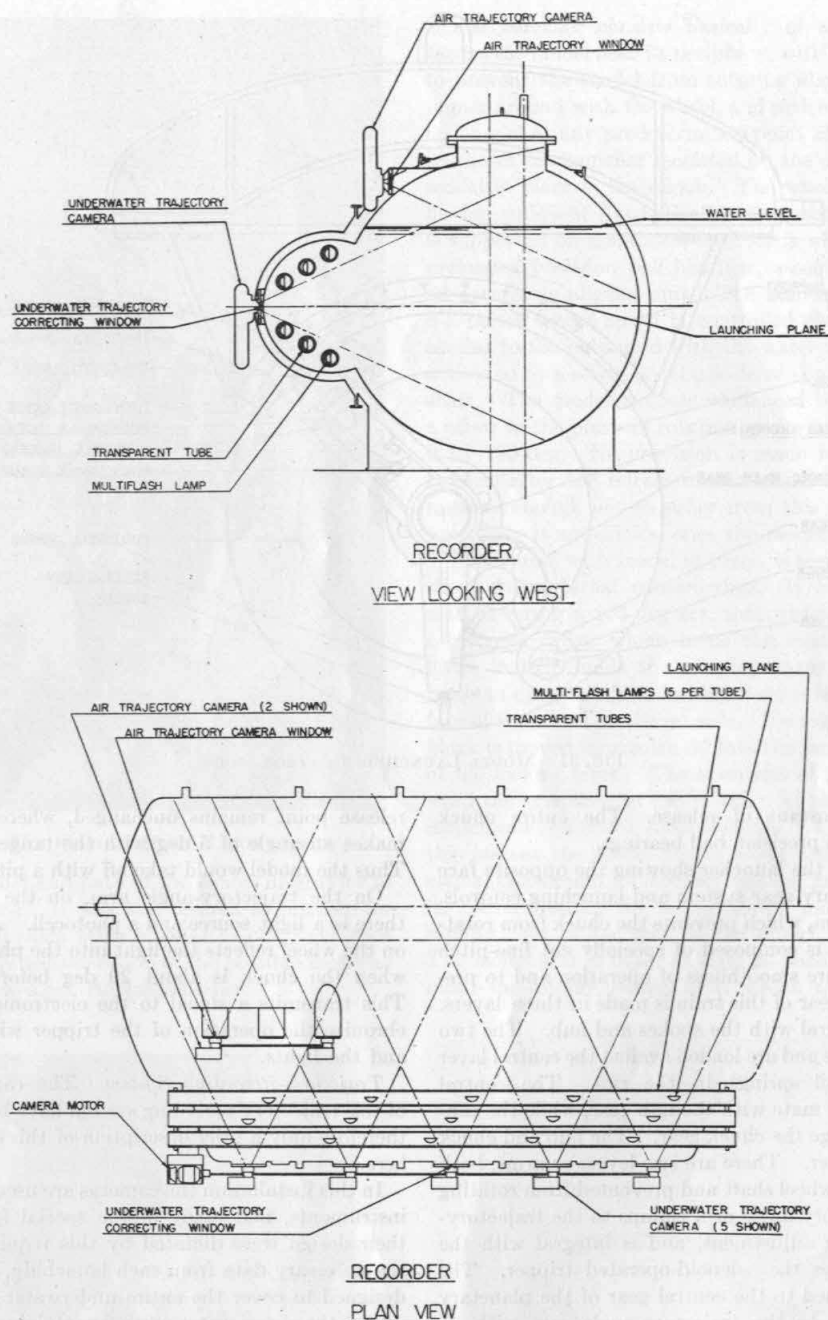


FIG. 32 ARRANGEMENT OF CAMERAS AND THEIR OVERLAPPING FIELDS OF VIEW

age makes it possible to use stereoscopic technique for the analysis of the recorded data to obtain five components of the motion, namely, longitudinal, lateral, and vertical movements, and rotation in the horizontal and vertical planes. Each camera is rigidly attached to a flanged opening in the tank shell and looks into the tank through a small window.

In the case of the underwater cameras, if a plane window were used, the result would have been reduction of the field of view due to refraction of the light in passing obliquely from the water to the air. This difficulty was overcome by using optically ground spherical windows, so positioned that the front nodal point of the camera lens is at the center of curvature of the window. Thus all primary rays pass through the interface at an angle of 90 deg and suffer no refraction; therefore there is

no distortion or reduction of field. However, the curved water interface is, in effect, a negative lens which increases the effective focal length of the system and shifts the focal plane. Thus, for example, if the distance from the lens to the object is actually 12 ft, the lens must be set for a focal distance of about 14 in. when used with the spherical window. This shift in focal plane causes a field reduction of 4 per cent, compared to a field reduction of 29 per cent which would have resulted if a plane window were used.

The design requirement of a maximum rate of 3000 frames per sec made it necessary to use a continuous motion of the film because of the obvious difficulty involved in starting and stopping the film 3000 times per sec. Also, a rather high film speed was mandatory to provide a reasonable frame height. A speed of

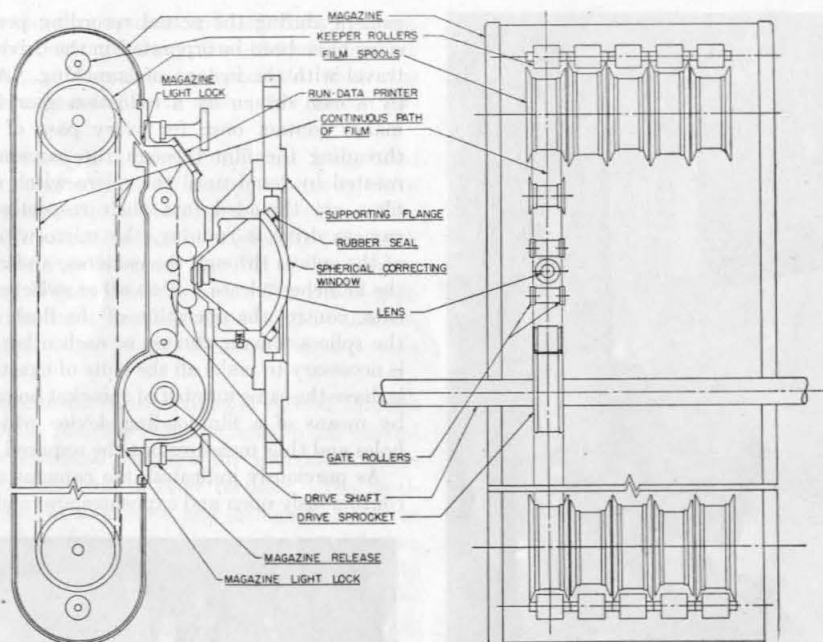


FIG. 33 UNDERWATER CAMERA WITH FILM MAGAZINE, SPHERICAL WINDOW, AND MOUNTING FLANGE

31.25 fps was selected, which at 500 frames per sec gives a standard 35-mm frame height of $\frac{3}{4}$ in., resulting directly in a projectionable motion-picture film. At the higher rates of 1000, 1500, and 3000 frames per sec, the frame heights are, respectively, $\frac{3}{8}$, $\frac{1}{4}$, and $\frac{1}{8}$ in. This high film speed makes it necessary to use extremely short exposures, of the order of two microsec, which are obtained by using flash lamps of the Edgerton type.

Fig. 33 is a drawing of one of the underwater cameras, with film magazine, spherical window, and mounting flange. The lens is a 1-in., $f/2.3$, Bausch and Lomb Baltar. To prevent friction, the film is guided through the focal plane by rollers instead of the usual pressure-plate arrangement. The film magazine may be detached from the camera and tilted to a horizontal position for loading. A thirty-two-ft length of film, sufficient for a single run, is stored in the magazine in a number of passes over the two sets of idler spools. The ends of the film, which extend through the light locks, are spliced together to form a slack loop about 2 ft long outside the magazine. Fig. 34 shows the arrangement of the film inside the magazine, and Fig. 35 shows a loaded magazine with the exposed loop containing the splice.

The loading operation is completed by tilting the magazine into the vertical position and threading the loop over the guide rollers and drive sprocket of the camera. With the film thus arranged in a continuous belt, it is possible to bring it up to speed gradually, expose it, and slow it down again without wasting any film or using long leaders.

All the cameras are driven through line shafting by a single synchronous motor.

Fig. 36 shows the underwater cameras and the driving motor. Fig. 37 is a close-up of the motor. To provide gradual acceleration and deceleration of the film, the motor housing is mounted in trunnion bearings so it may rotate, and the power to it is brought in through slip rings on its left-hand face. Two electrically operated brakes are provided, one to stop the shaft and one to stop the housing. To start the motor, the shaft brake is clamped, the housing brake is released, and the power is applied. The housing then begins to rotate, comes up to speed, and is

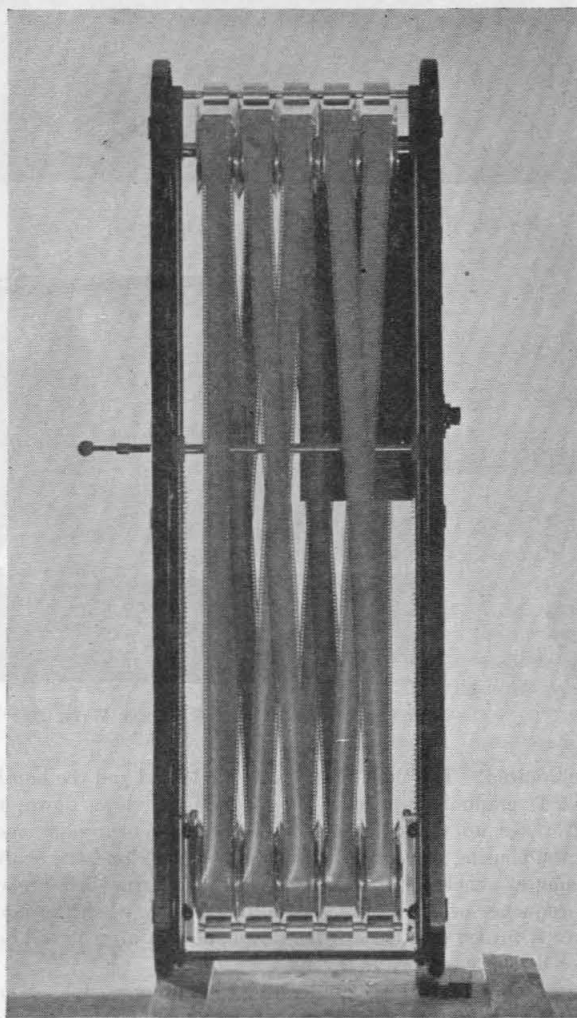


FIG. 34 BACK VIEW OF FILM MAGAZINE WITH COVER REMOVED

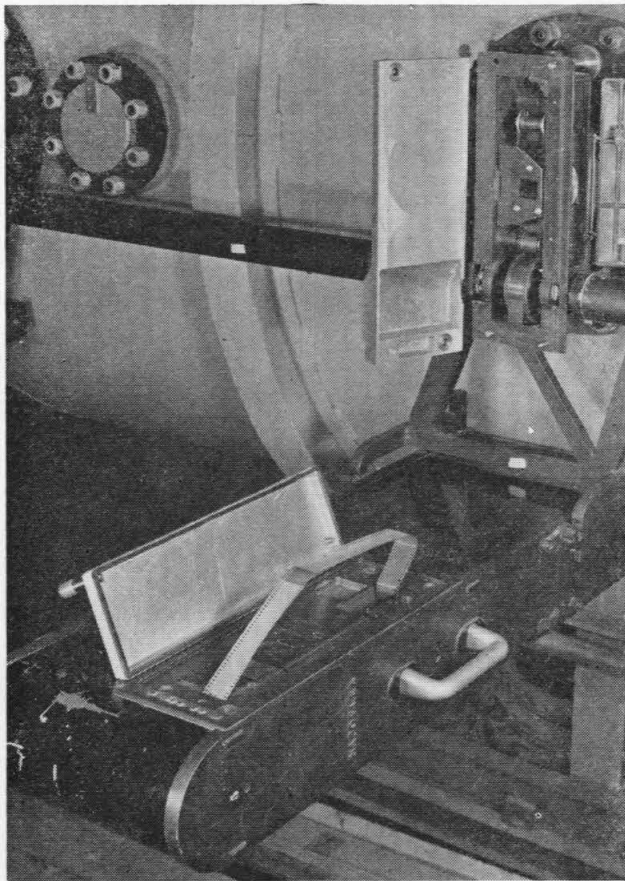


FIG. 35 LOADED MAGAZINE WITH THREADING LOOP

camera during the actual recording period. Therefore provisions have been incorporated in the drive to synchronize the film travel with the instant of launching. A microswitch, actuated by a cam driven by a reduction gear from the camera shaft, makes contact once for every pass of the film belt. Before threading the film through the cameras, the camera shaft is rotated by hand until the microswitch closes, and then all the films are threaded into their respective cameras. When the camera drive is running, the microswitch signals each passage of the splices through the cameras, and controls the operation of the launcher release. Two other switches, actuated by the same cam, control the operation of the flash lamps. To insure that the splices remain abreast of each other throughout the run, it is necessary to make all the belts of exactly the same length, that is, have the same number of sprocket holes. This is accomplished by means of a film-loading device which counts the sprocket holes and thus measures out the required length.

As previously indicated, the cameras are operated with lenses continuously open and exposures are made by illuminating inter-

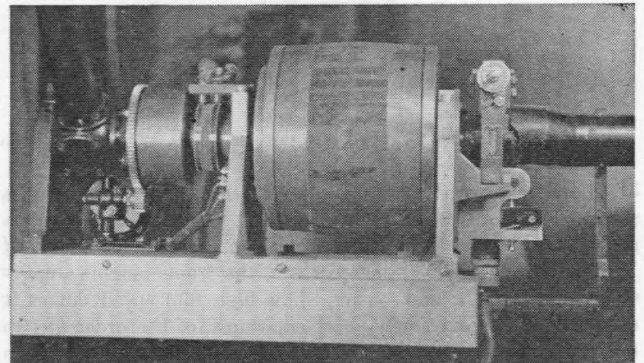


FIG. 37 CAMERA-DRIVE MOTOR WITH COVER REMOVED

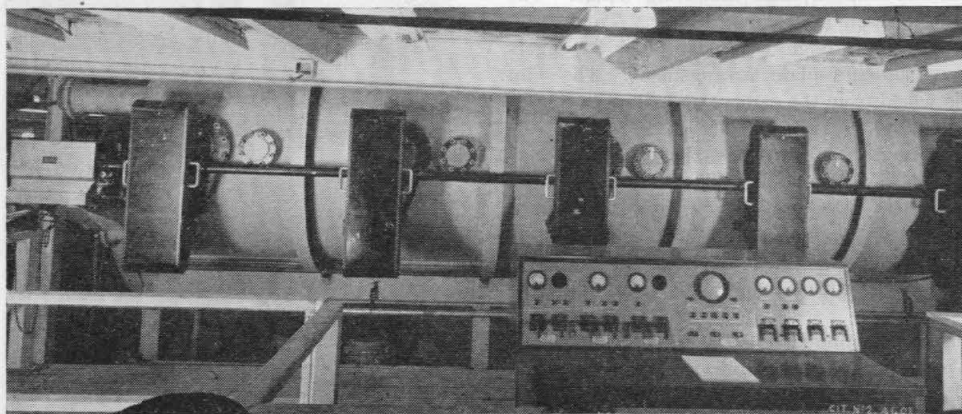


FIG. 36 UNDERWATER CAMERAS WITH DRIVE SHAFT AND MOTOR; CONTROL PANEL IN FOREGROUND

synchronized. The shaft brake is then released and the housing brake is gradually applied. As the housing slows down, the shaft takes up the difference between the synchronous speed and the housing speed, and, when the housing stops, the shaft is running at synchronous speed. By means of time-delay relays, this sequence of events proceeds automatically when the motor power is turned on. In slowing down the film after it had been exposed, this sequence is reversed.

It was noted before that in loading the film magazine, about 2 ft of film containing the splice is exposed to light. It would be undesirable to have this portion of the film pass through the

intermittently the interior of the tank with flash lamps. A simple computation, involving the speed of the film and the projection ratio required for analysis, showed that the maximum effective flash duration usable would be about 2 microsec if sufficiently sharp images to give the required accuracy of measurement were to be obtained. This is approximately $1/10,000$ of the exposure time normally used in motion-picture photography. This means that extremely high light intensity is required, which could be obtained only by using a large battery of synchronized flash lamps. The assistance of Dr. Harold Edgerton of the Massachusetts Institute of Technology was enlisted because of

his wide experience in the development and use of flash lamps. The system consists of a battery of from 30 to 42 flash lamps, all operated simultaneously. Measurements indicate that the individual lamps are synchronized with each other within less than $\frac{1}{4}$ microsec.

Each lamp consists of a quartz tube about 8 in. long, filled with xenon, hydrogen, and a trace of radium bromide, with two metallic electrodes sealed into the ends of the tube. Two types of lamps are used. One consists of a straight tube with an aluminized lucite reflector designed by Dr. I. S. Bowen, Director of the Mount Wilson Observatory. The other type consists of a helical tube in a headlight-type sealed-beam reflector with smooth lens. Figs. 38 and 39 show the two types of lamps.

The power for the operation of each light is carried through an individual coaxial cable running from the light to the control panel. Each light is operated through an individual surge circuit which receives power from a large rectifier. The rectifier delivers direct current at 4000 volts, and the lights operate at twice this value through a voltage doubler incorporated in the circuit. The power consumption of each light is approximately 0.8 joules per flash. Thus at 3000 flashes per sec, the battery of 30 lamps requires a continuous input of approximately 80 kw. It must be remembered that at this speed the lights are lit only about $\frac{1}{200}$ of the time. This means that the power input during the period of illumination is at the rate of better than 16,000 kw. The heat generated in the tubes themselves limits the length of operation, since the tubes get quite hot and will collapse if they are operated too long. At flash rates of 1000 per sec, and above, the only significant heat dissipation is through radiation. Experiments have shown that 3600 flashes per run are the maximum that can be employed for successful high-speed operation.

A typical experiment is carried out as follows:

The camera magazines are loaded and attached to the cameras. The model is installed in the launcher, the desired trajectory and pitch angles are set, and the launcher is lowered into the tank by closing the hatch cover upon which it is mounted. The required air pressure, if below atmospheric, is adjusted by means of the vacuum pump. The launcher wheel is brought approximately to speed by manual control and is then put on automatic control which holds it exactly at the desired speed. The camera motor is turned on and the film comes up to speed automatically. The operator now starts a sequence necessary to launch the model by pressing and holding down the launching button. This operates the first of the three interlocks. The second interlock is actuated by the microswitch on the camera drive as the exposed film splices finish passing through the focal plane of the camera, and the third and final interlock, which trips the model and launches it, is actuated on the next revolution of the launching wheel after the film interlock operates. The flash lamps begin to function simultaneously with the release of the model and continue to flash until the entire length of film is exposed, at which time the lamps are automatically cut off. The equipment is then automatically shut down in reverse order of the starting sequence.

The camera motor runs at a constant speed of 31.25 rps. When the launcher runs at any multiple of that speed, the passage of the film splice through the camera and the passage of the model past the launching point occur with a fixed phase relation between them and may never coincide, in which case it would be impossible to launch the model. Provision is made therefore for changing the phase relation. This is done by rotating slowly the camera motor housing by means of a small

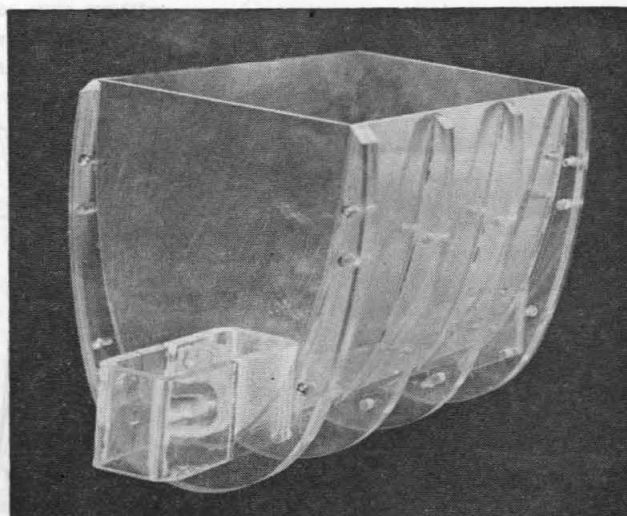


FIG. 38 FLASH LAMP AND LUCITE REFLECTOR

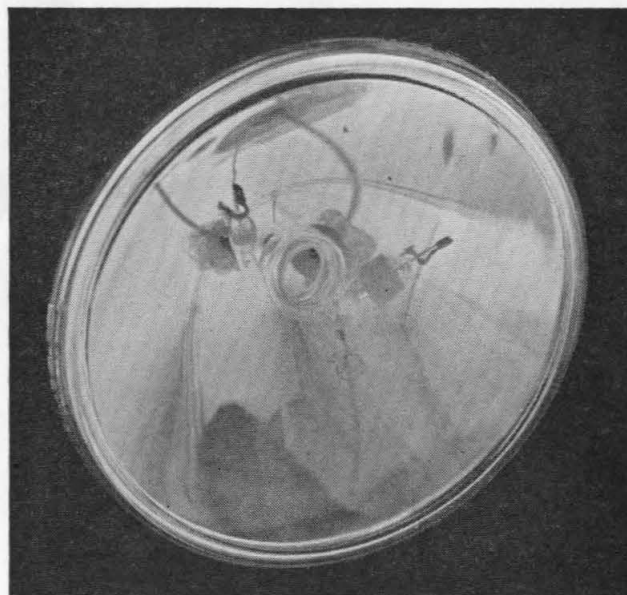


FIG. 39 HEADLIGHT-TYPE LAMP

electric motor geared to the housing brake. This may be seen in the lower left side of Fig. 37.

Data-Analyzing System. The basic principle of the analyzer is that it is essentially a duplicate of the recording system. Projectors take the place of the cameras and a movable screen replaces the model. All of the films from one run in the launching tank are placed in the corresponding projectors with the film strips synchronized so that the corresponding frames taken at the same time will be projected at the same time. The film drive of the projectors is a continuous shaft so that once the film strips are synchronized, they remain so during the projection of the entire run. Fig. 40 shows a line diagram of the analyzer system. It represents a point on the trajectory in which the projectile was in the field of view of cameras Nos. 2 and 3, so that projectors Nos. 2 and 3 are projecting the two images into the analyzer space. It is obvious that there is only one position in this space in which the two images will coincide. The exploring screen of the analyzer is then maneuvered until the two images both fall on it. Additional maneuvering causes the two images to fuse into one. This requires movements of the screen in three

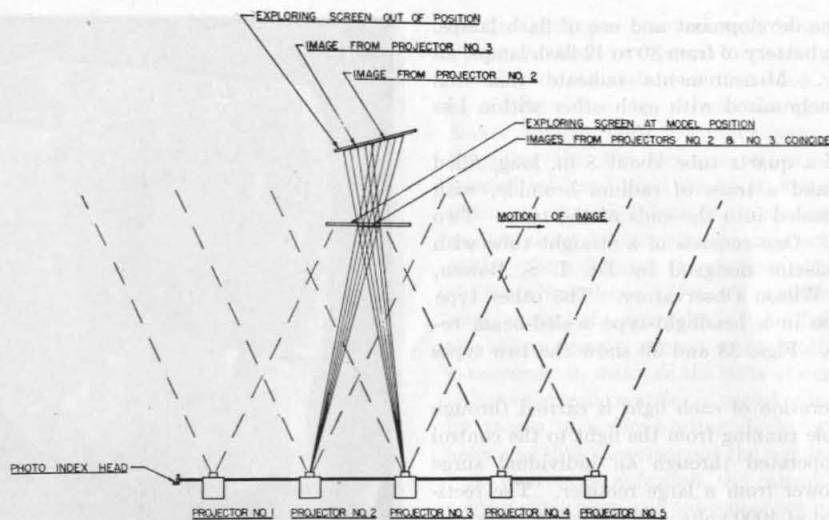


FIG. 40 SCHEMATIC DRAWING OF ANALYZER SYSTEM

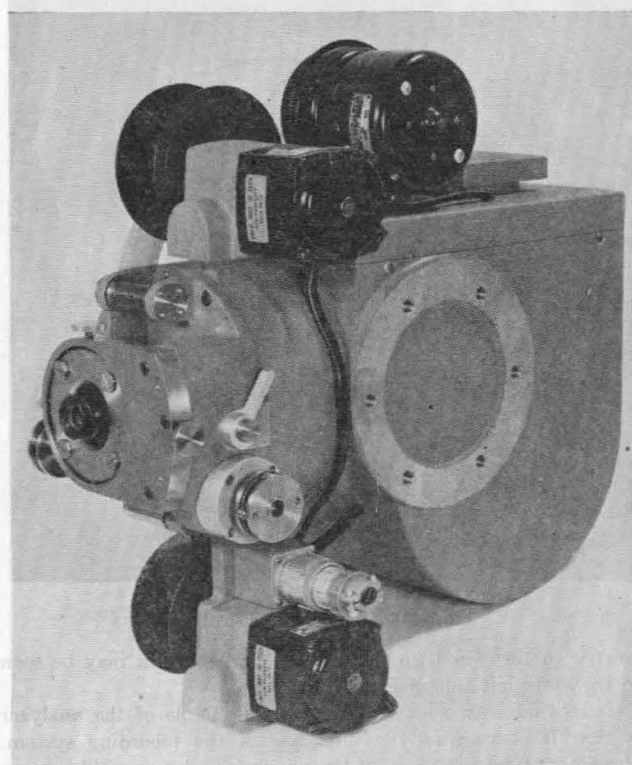


FIG. 41 ANALYZER PROJECTOR

linear directions and also two angular motions. These movements are transferred to a battery of counters. When the screen is finally in the exact position required for the precise fusing of the images, the counters indicate the position of the projectile in space corresponding to that pair of photographs. The analyzer is built to a scale of one half that of the tank and recording equipment.

The projectors for this analyzer are precision instruments. As a first step in their construction, lenses were procured in matched pairs. One lens of the matched pair is used in the camera and the other lens in the corresponding projector. The gate mechanism is designed to hold the film exactly in the focal

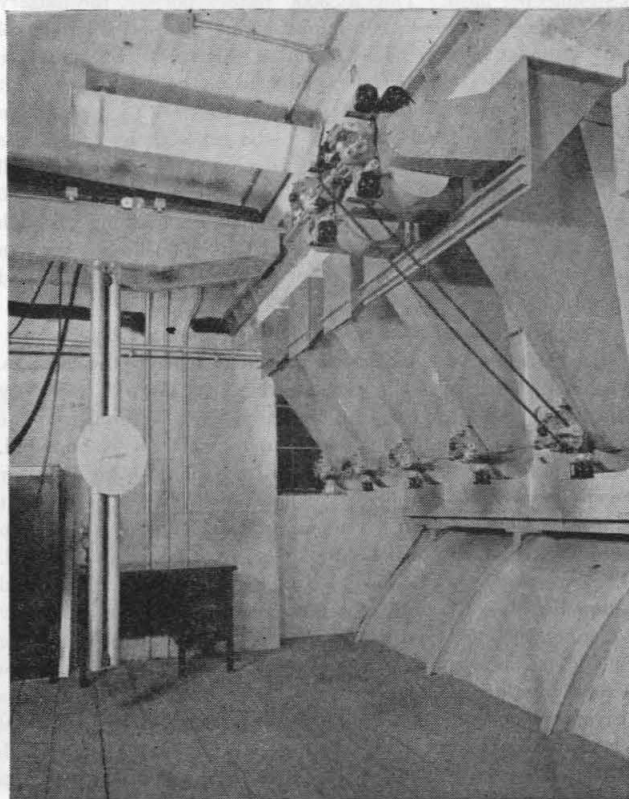


FIG. 42 DATA-ANALYZING EQUIPMENT

plane. The light source is kept at as low an intensity as is consistent with the accuracy of the readings that are required, in order to eliminate as much heat as possible which might affect both the dimensions of the film and those of the optical system. The temperature is controlled further by the employment of water cells and individual air cooling. Fig. 41 shows one of the projectors. To check the location of each frame, use is made of a series of reference marks on the rear wall of the launching tank. These marks are reproduced on a background screen at the rear of the analyzer, and before making a measurement a check is made to see that the images of the marks from the films in the

projector fall on the corresponding marks on this screen.

The exploring screen is a small disk with a half-model attached to it so the final projection is on a curved surface similar to the one photographed. The screen is carried on a mechanical transport which provides three linear and two angular motions. A carriage which spans the width of the room rides on longitudinal overhead rails. On this carriage is a pair of transverse rails on which travels a smaller carriage. Both carriages have rack-and-pinion drives. A pair of vertical guide tubes with a screw drive are suspended from the transverse carriage. These are arranged so they can be rotated in azimuth to provide one of the two angular motions. The other angular motion is obtained by rotation of the circular screen in its own plane. Selsyn repeaters and mechanical counters are used as position indicators to transmit the information to the operator's desk. Fig. 42 shows the data-analyzing equipment. It is planned to add another set of selsyn repeaters to operate recording pens at a plotting table where the three co-ordinates and two angles will be plotted against time.

CONCLUSIONS

In addition to the major pieces of equipment just described, the laboratory has available considerable auxiliary equipment which measurably widens the scope of work that can be undertaken. Three service facilities are also deserving of mention since they are of great utility to all of the laboratory research programs. These are the electronics laboratory, a photographic laboratory capable of processing both still and 16- and 35-mm film, and a precision instrument and model shop.

It is quite clear from the foregoing description that the fundamental interest of the laboratory is in basic research over a rather wide section of the field of hydrodynamics. At the same time the equipment is well adapted to yield accurate information on the characteristics of specific devices or machines. Much of the major equipment has been put into operation quite recently. Therefore it is hoped that this description of the laboratory will prove to be only the introduction to a series of studies in the field of hydrodynamics that will be referred by the laboratory to the engineering profession.